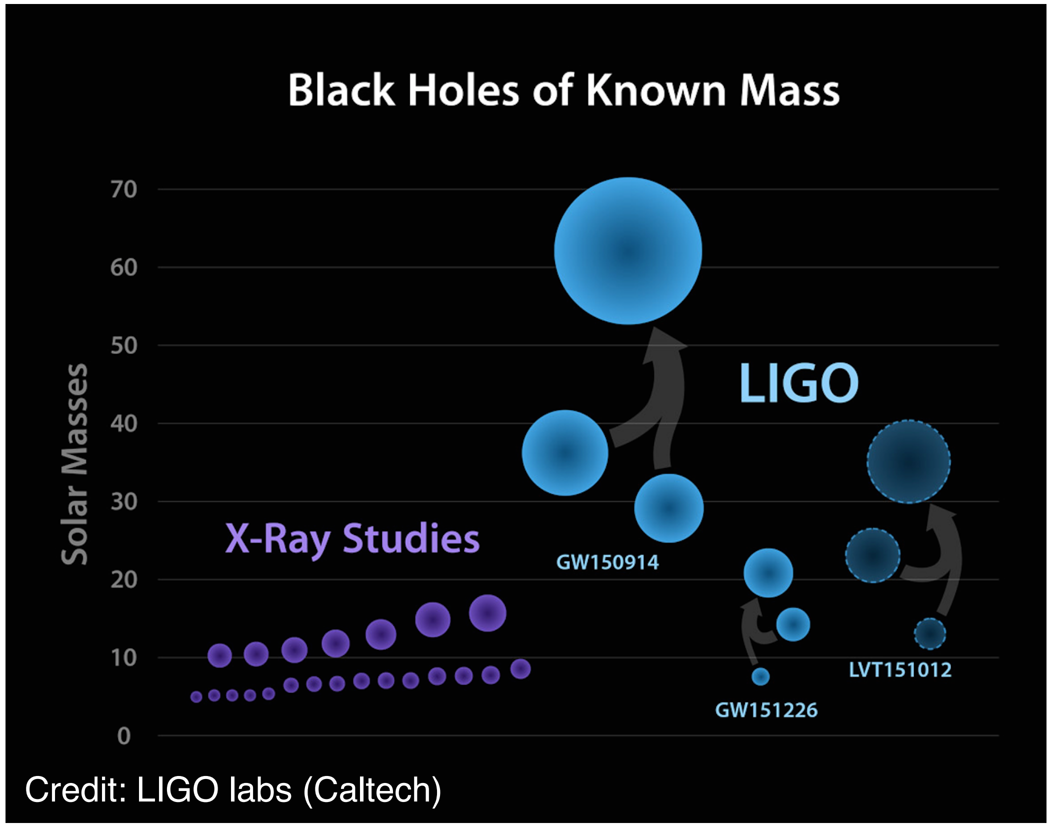
VIR-0624A-17

Follow the roar and chirp: characterising compact object mergers with gravitational-wave (GW) and electromagnetic (EM) observations

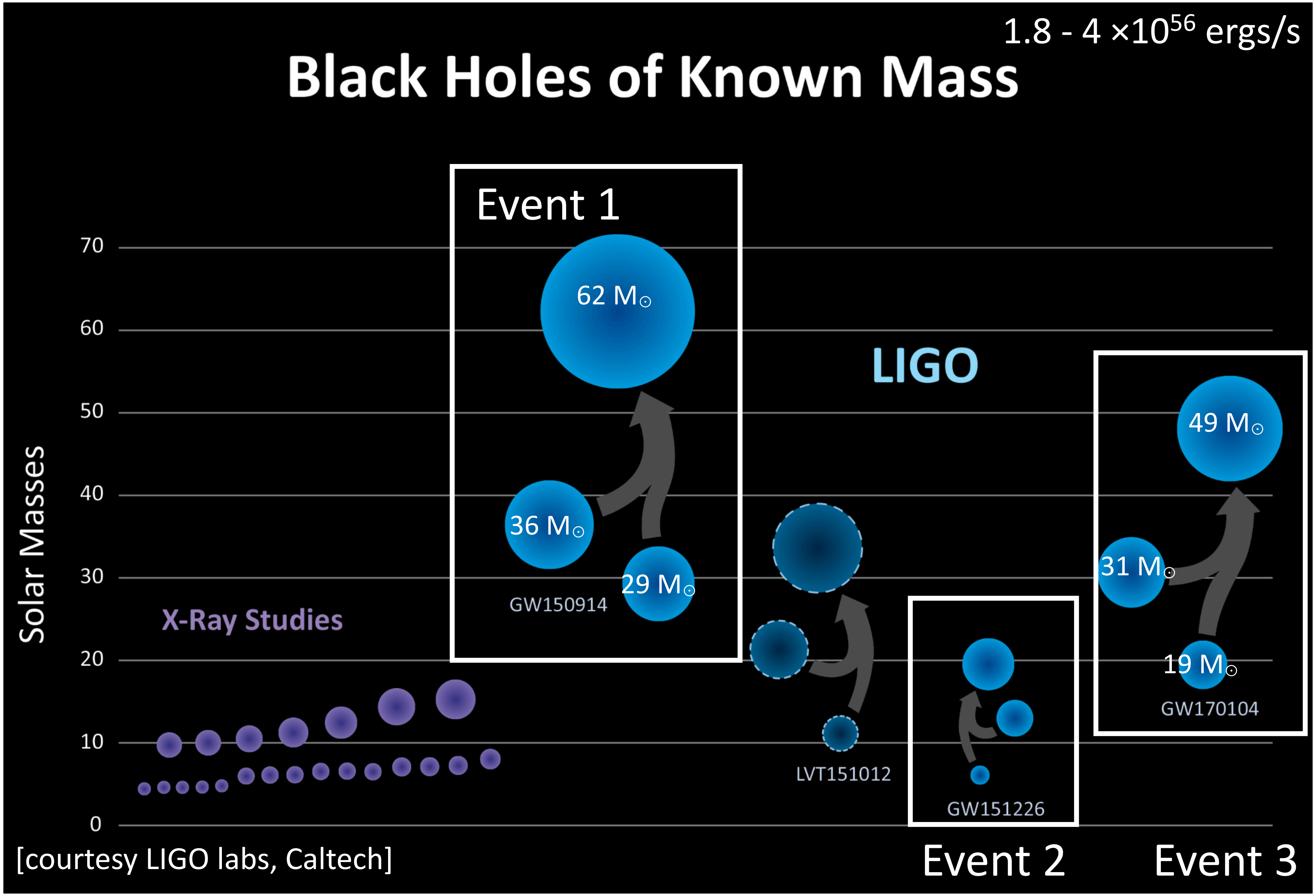


Credit: LIGO labs (Caltech)

Samaya Nissanke
Radboud University, Nijmegen, the Netherlands

TeVPA conference, Columbus, Ohio, 11th August 2017

Black Holes (BHs) exist & exhibit unexpected diversity!

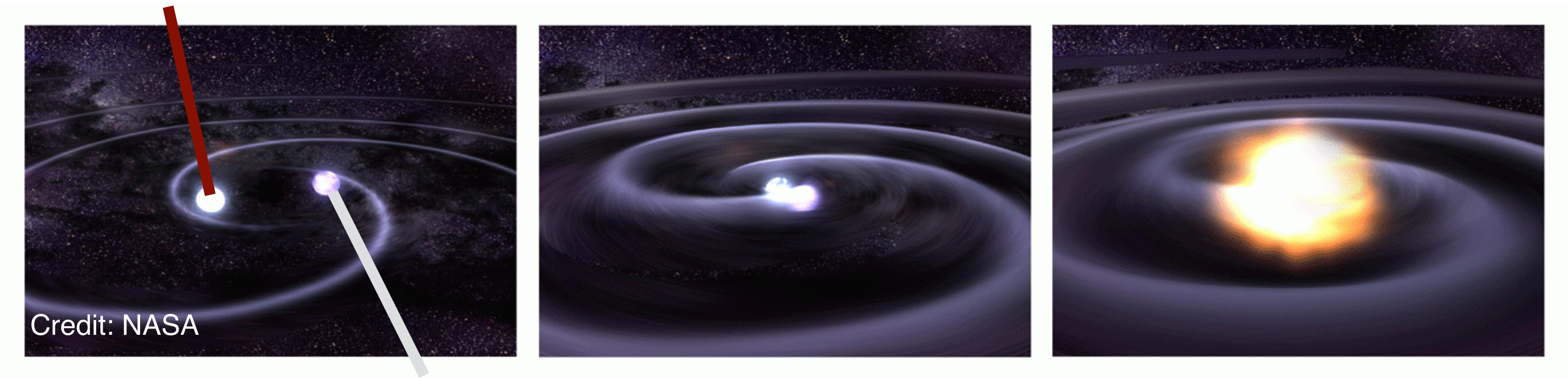


[courtesy LIGO labs, Caltech]

Signal-to-Noise Ratio (SNR) of 24 SNR of 13 SNR of 13

Compact object merger in matter or plasma is the next discovery in GWs

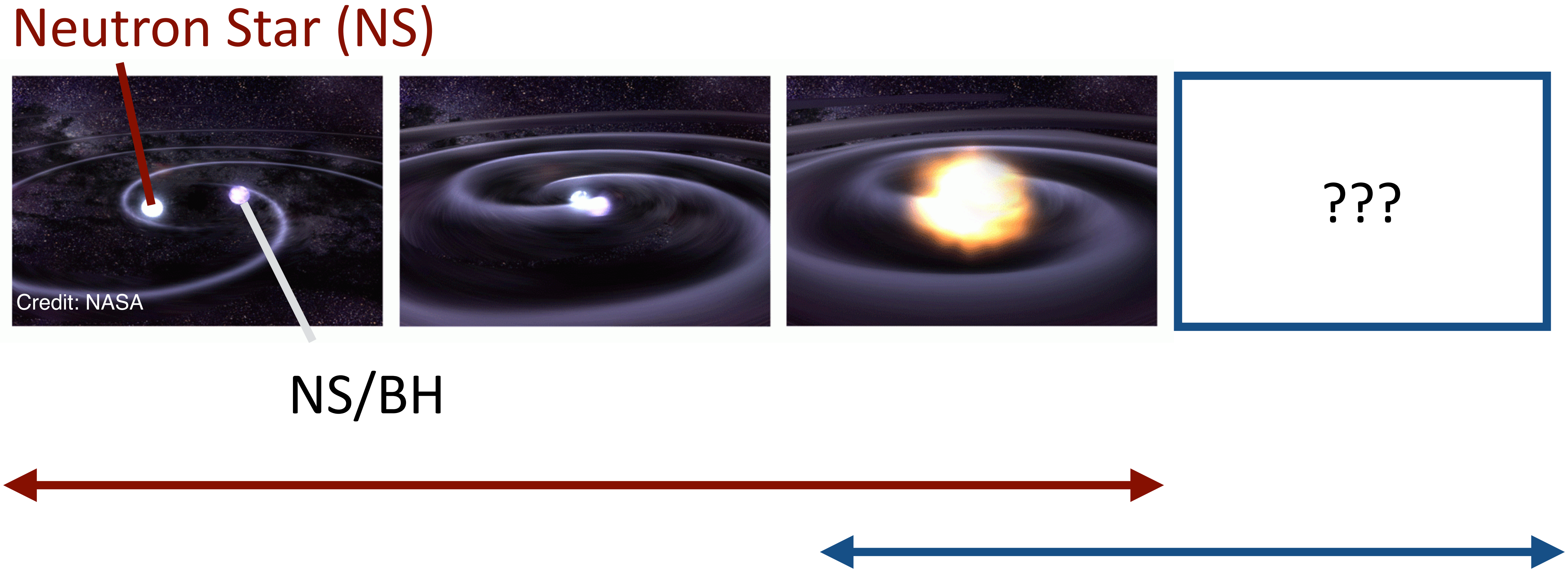
Neutron Star (NS)


Credit: NASA

NS/BH

???

Electromagnetic (EM) radiation probes fundamental physics in strongly curved dynamical spacetimes



Credit: NASA

Neutron Star (NS)

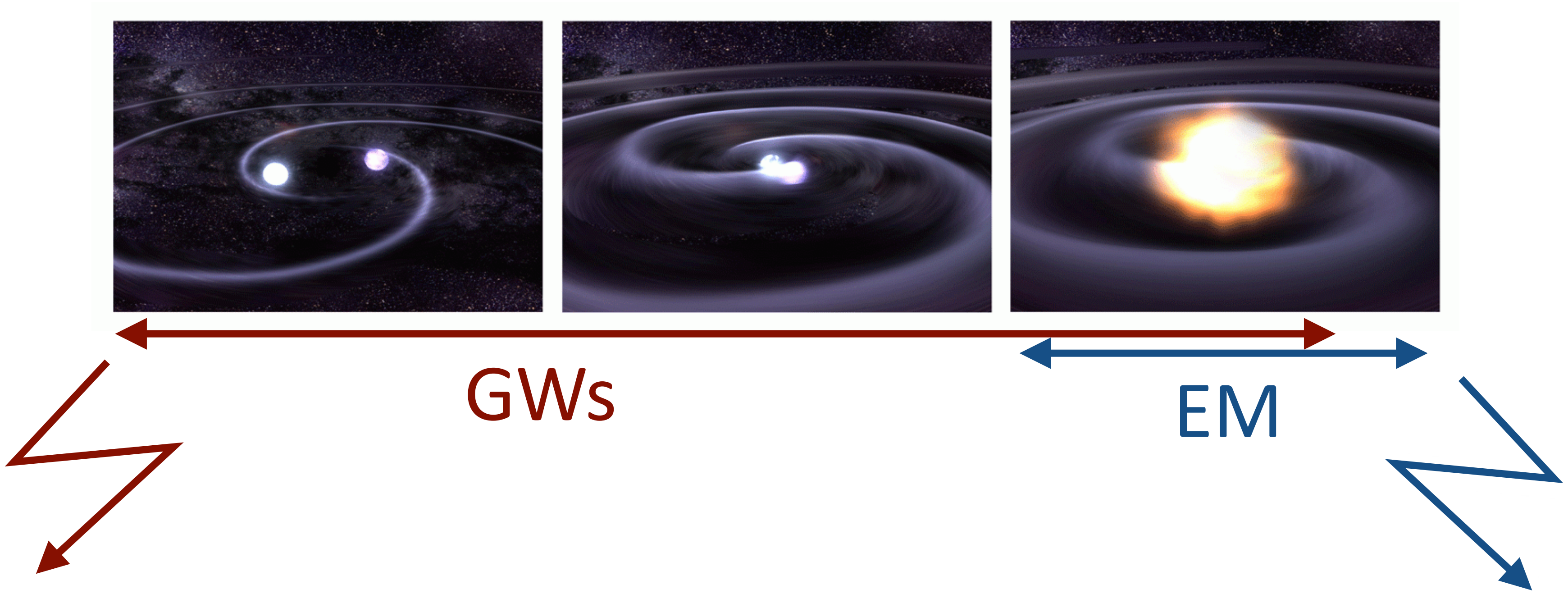
NS/BH

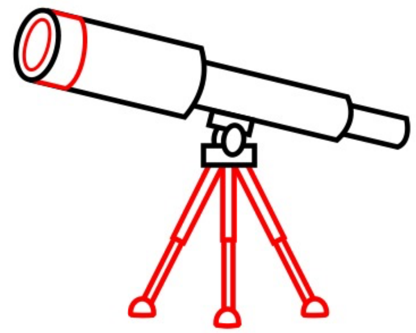
???

Gravitational Waves
~ minute

EM counterpart:
delayed matter outflows ~10ms post-merger
EM emission is seconds- years

Game changer today: we can detect and measure GWs and multi-messenger radiation!





2018-2019 (LIGO+Virgo+…):

NS-NS: 0.04-100 year^{-1}

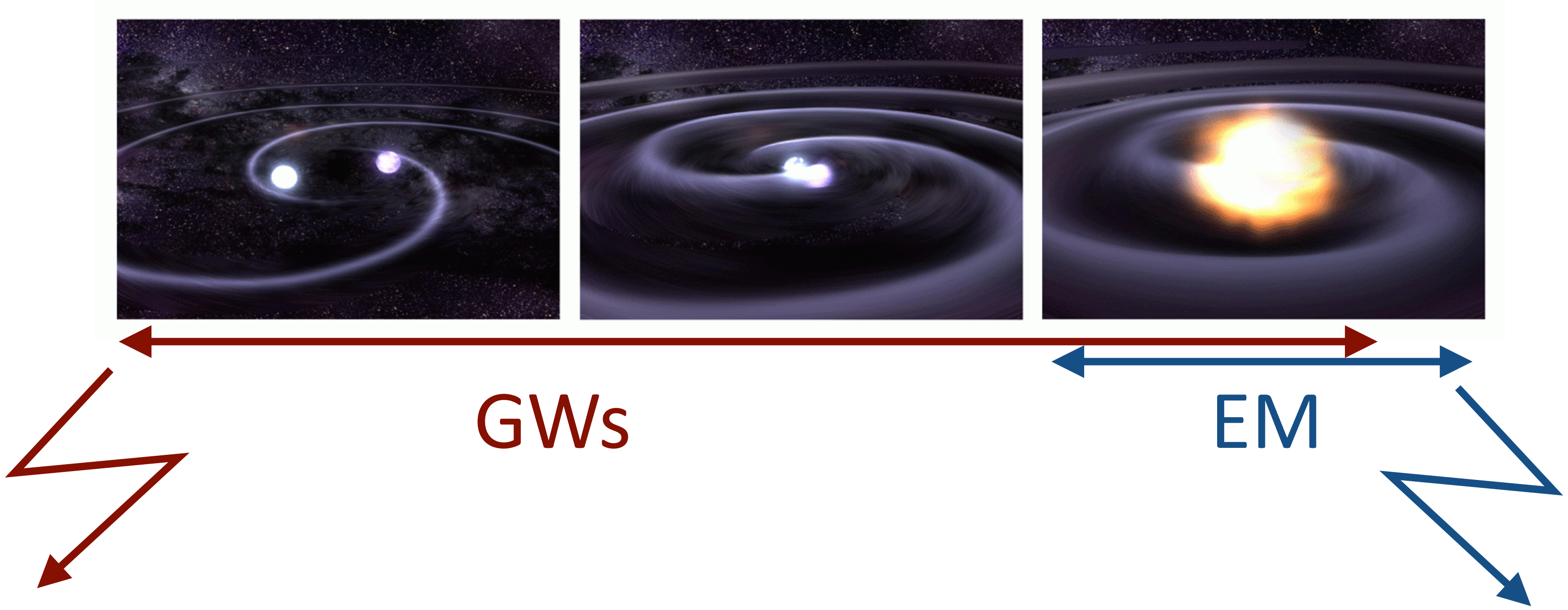
BH-BH: few to tens year^{-1}(mean)

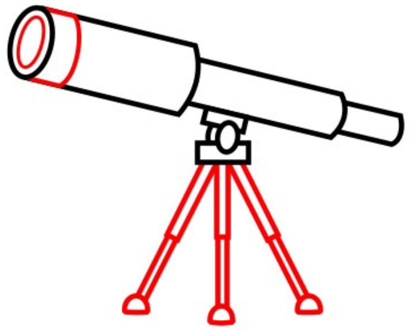
2017+:

Wide-field high-energy, optical, radio and high-energy neutrino telescopes

[LIGO Scientific and Virgo Collaborations (LVC),
Living Reviews in Relativity 19, 1, 2016 and PRX 6, 041015, 2016]

Two complementary probes on extreme-spacetimes: necessary to constrain astrophysics





Extract sources' <u>dynamic</u> and <u>fundamental (masses, spins) parameters</u>

Extract sources' <u>environment</u> and <u>energetics</u>

Plan of Talk

Part 1: Retrieving Black Hole (BH) parameters from GWs

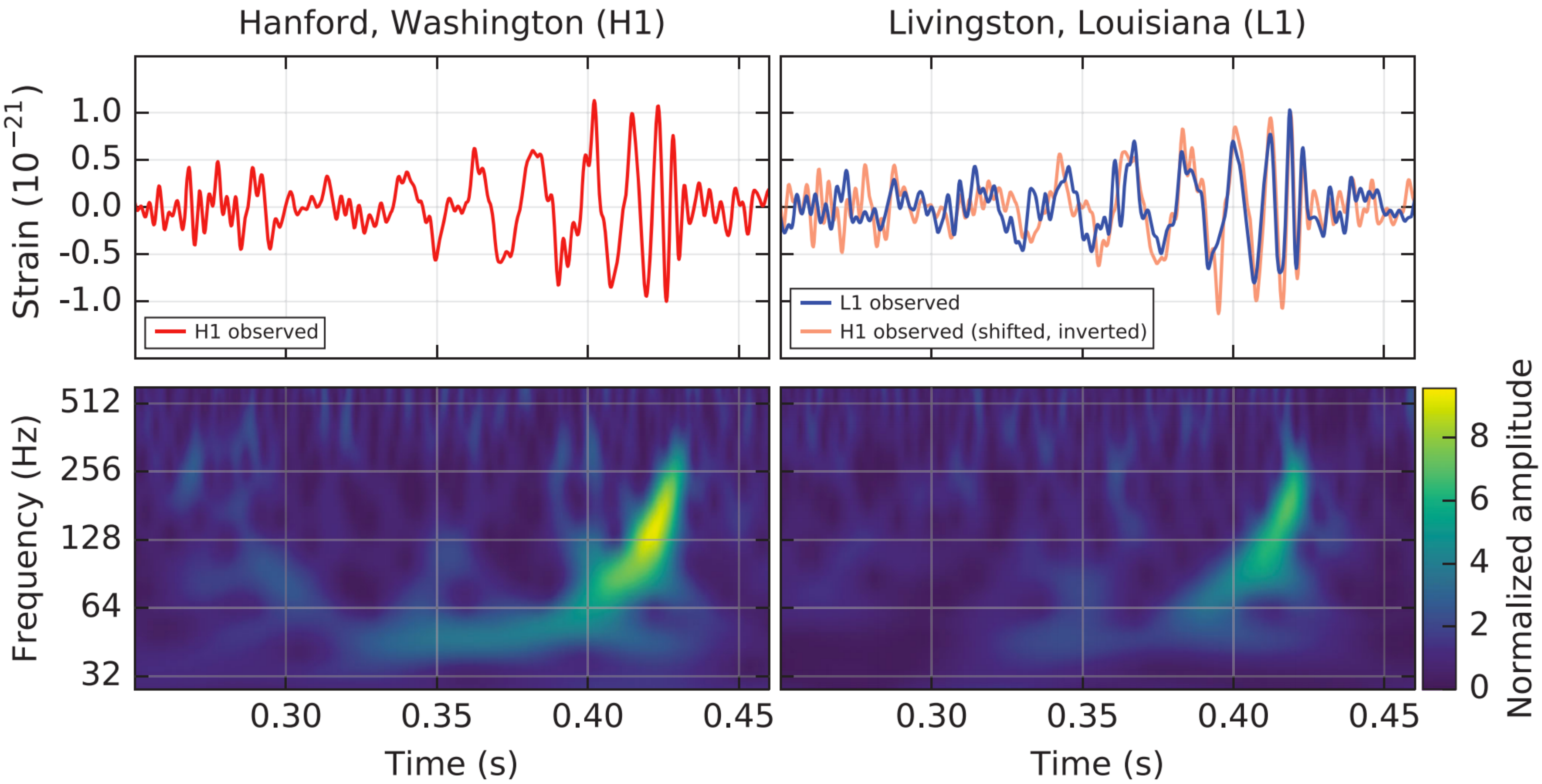
Part 2: EM follow-up for Binary BH mergers

Part 3: How to connect GWs to astrophysics with EM counterparts? (my own perspective)

Part I:
The Physics of GW observations and Retrieving BH parameters

First Observation of GWs

September 14 2015, 09:50:45.39 UTC

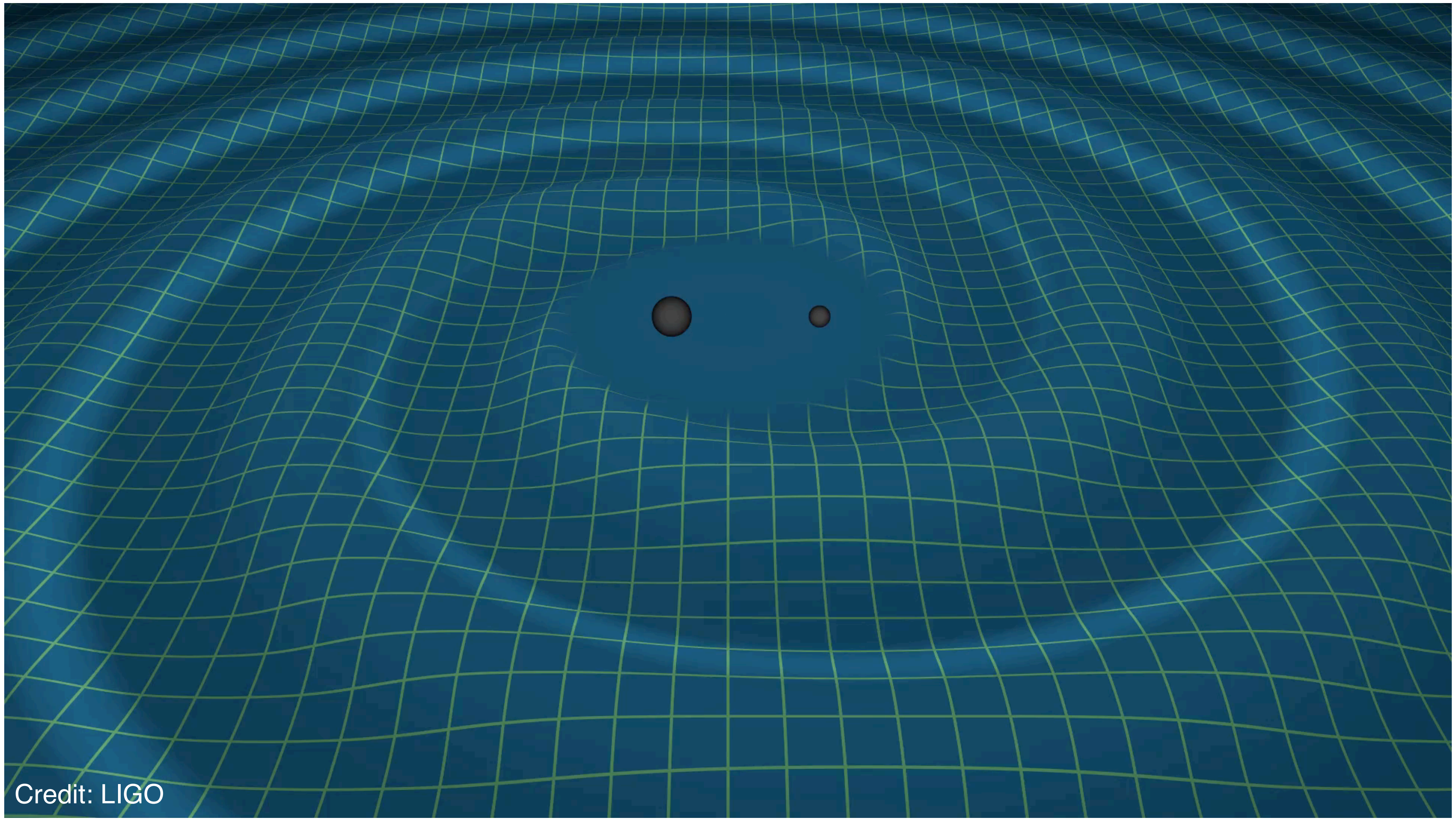


[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

⇒ fundamental properties of BHs, astrophysics (how and where?) & null tests of General Relativity

GWs are perturbations in spacetime curvature

Accelerating quadrupole matter sources



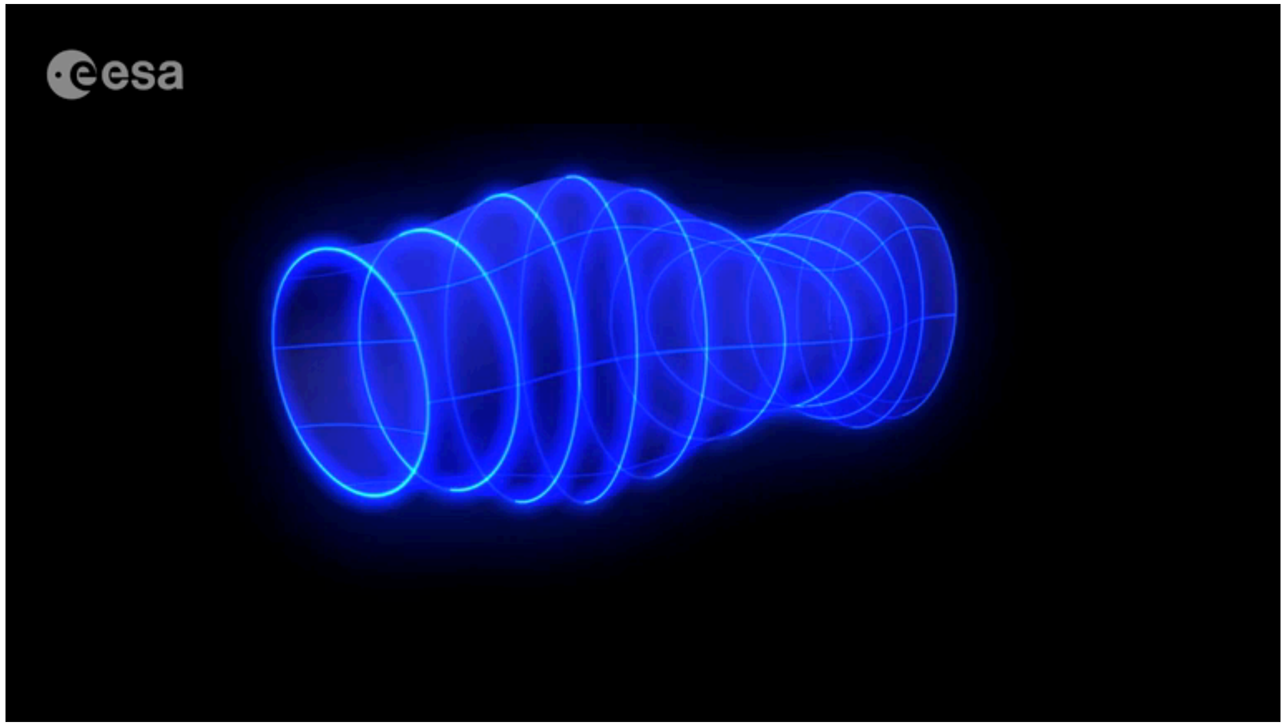
Credit: LIGO

Measurable GW strain h (t) ~ 1/distance

Newtonian Quadrupole formula (1916): $\mathcal{L} = \frac{G}{5c^5}\left\langle \frac{d^3 I_{ij}}{dt^3}\frac{d^3 I_{ij}}{dt^3}\right\rangle + \mathcal{O}\left(\frac{1}{c^7}\right)$

GWs are transverse tidal fields

Coherent, weakly interacting,
bulk dynamic properties of matter,
two polarizations h_+ and $h_\times$

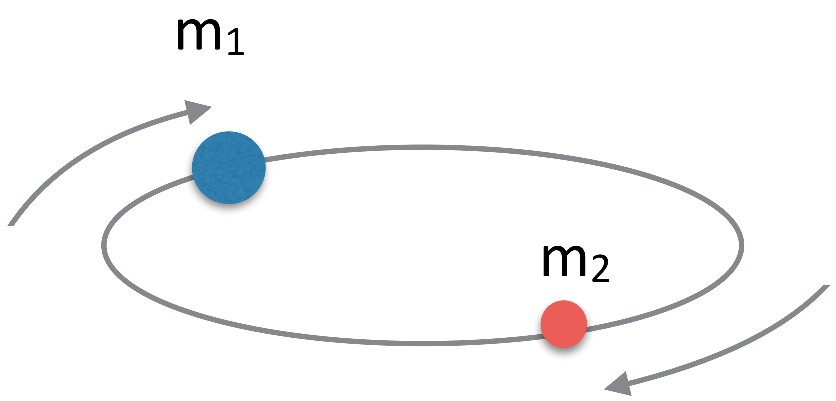


$$h \sim \frac{\Delta L}{L} \sim 10^{-21}$$

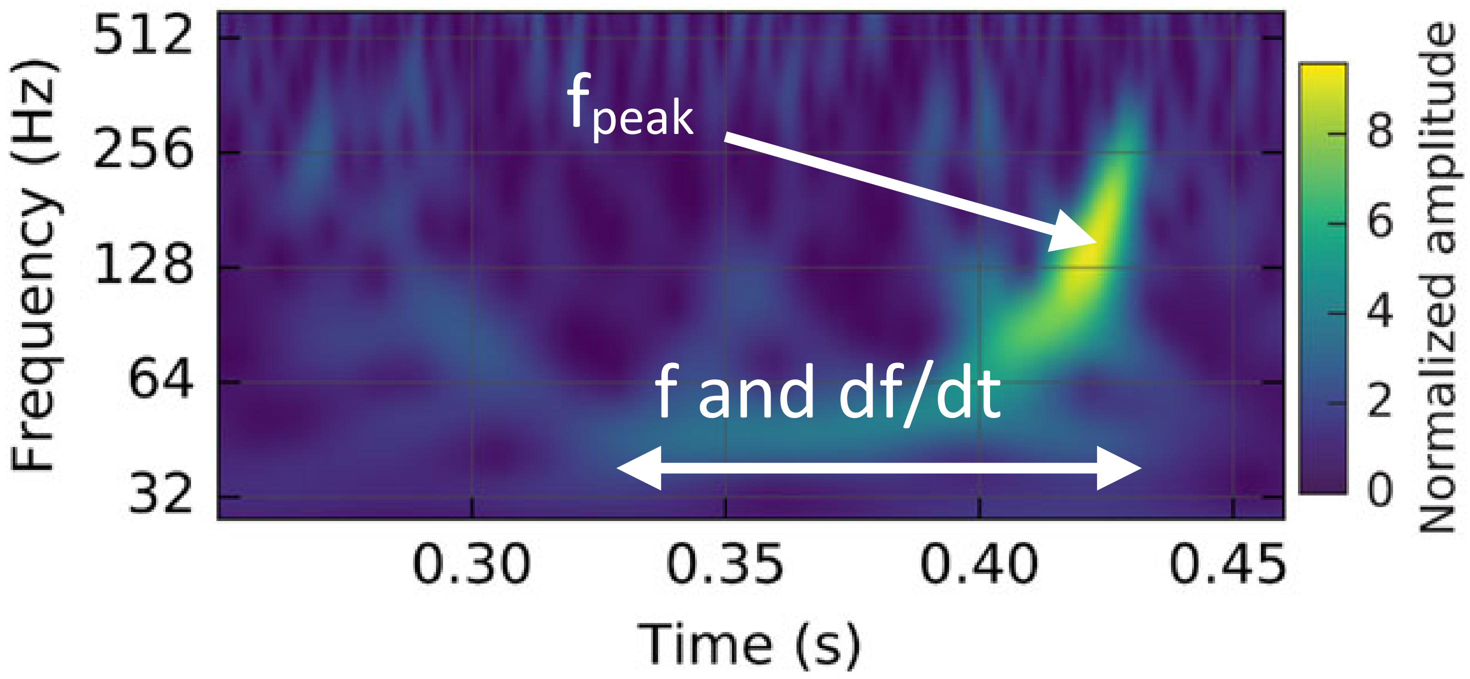

Credit: LIGO

advanced LIGO, Livingston

Simplest “Newtonian” model explains frequency chirp



$$\left(\frac{dE}{dt}\right)_{\rm rad} + \left(\frac{dE}{dt}\right)_{\rm orb} = 0$$



[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

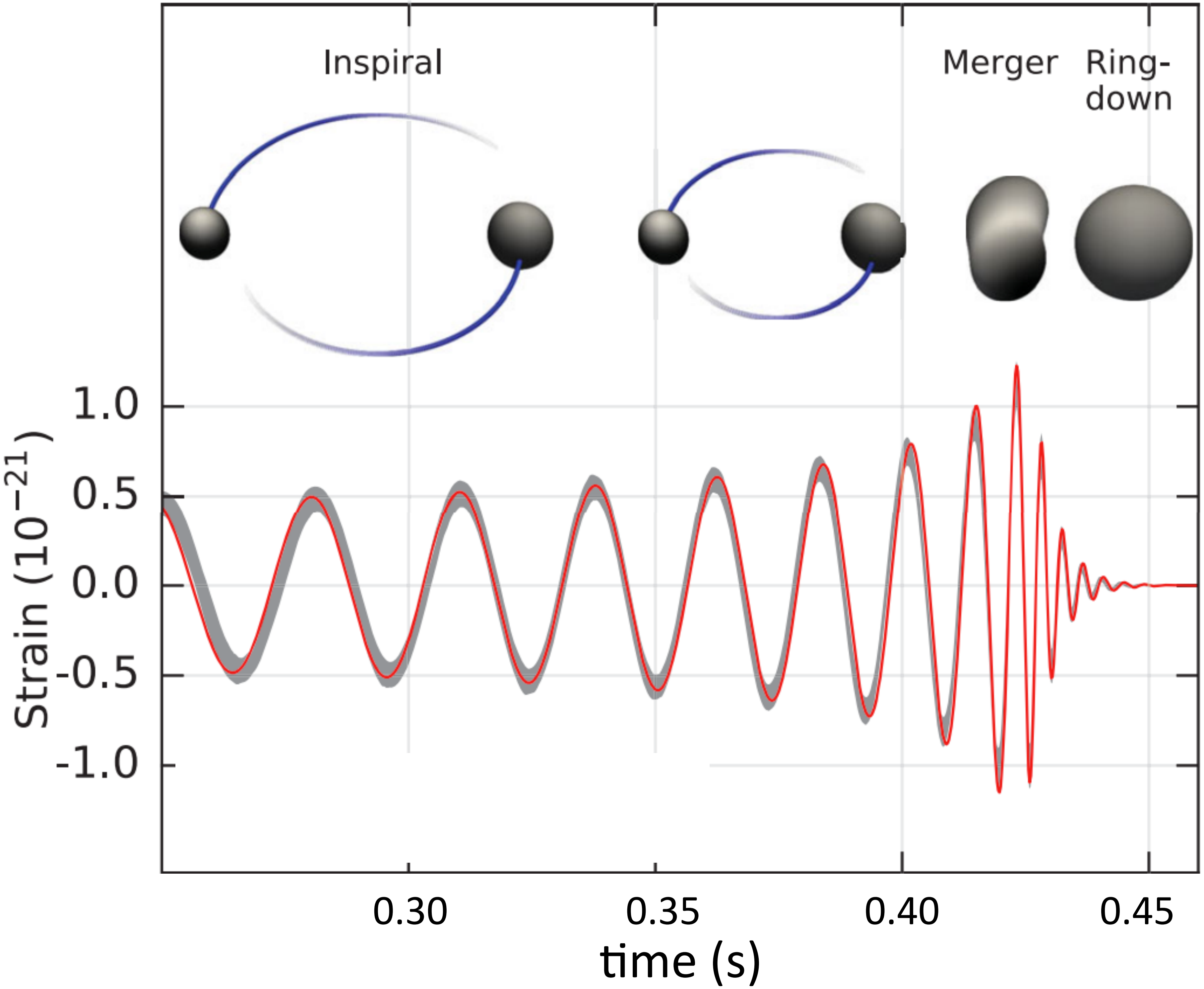
⇒ Frequency chirp:

$$\boxed{\frac{df}{dt} = \frac{96\,\pi}{5}\left(\frac{\pi\, G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}}$$

Chirp mass:

$$\boxed{\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}}$$

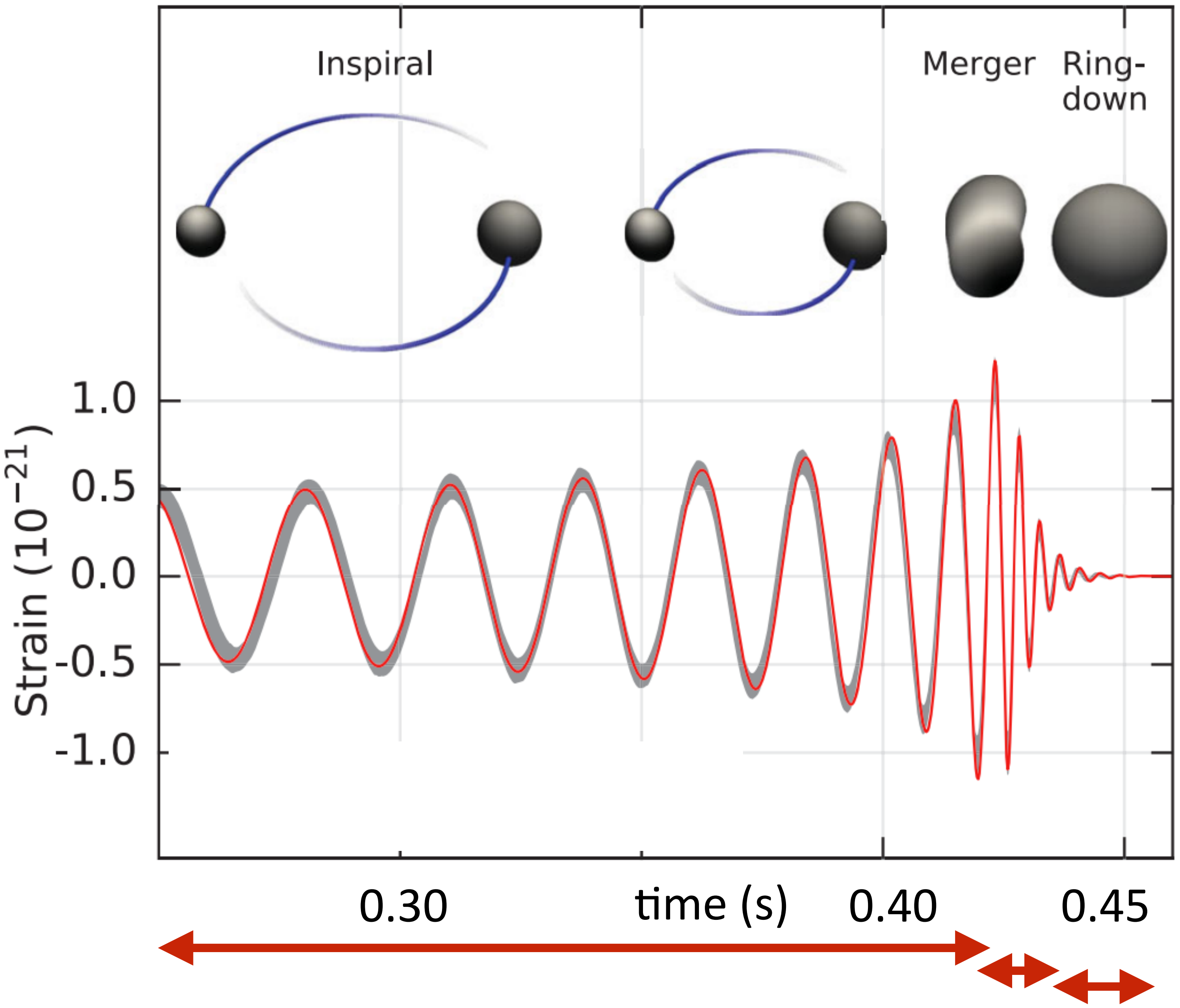
GW waveform encapsulates Binary Evolution



[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Chirp mass drives inspiral waveform

[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]



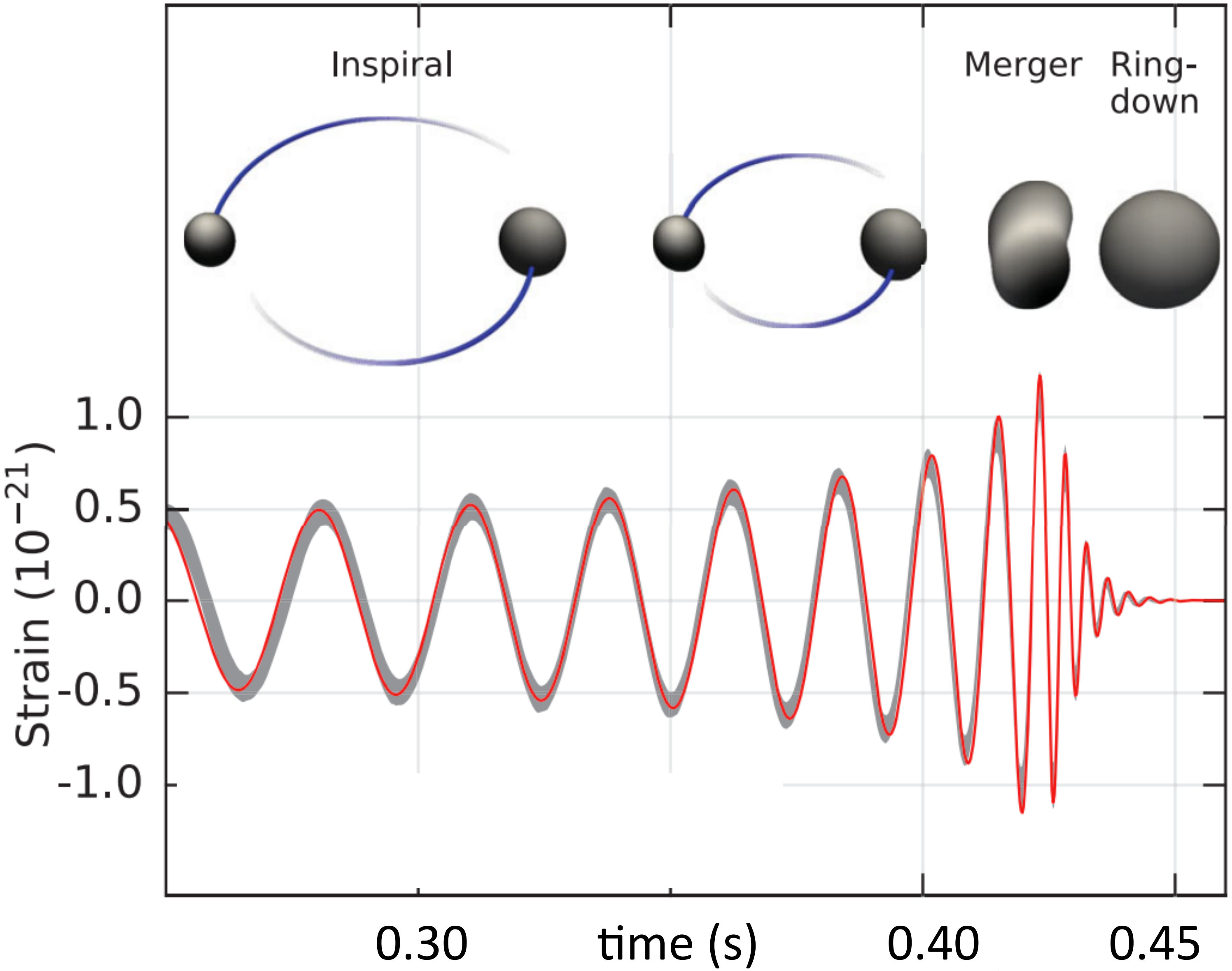
Inspiral ~ Chirp

Ringdown

<u>driven</u> by the chirp mass

… remnant mass & spin

Decades of theoretical effort in source modelling



post-Newtonian

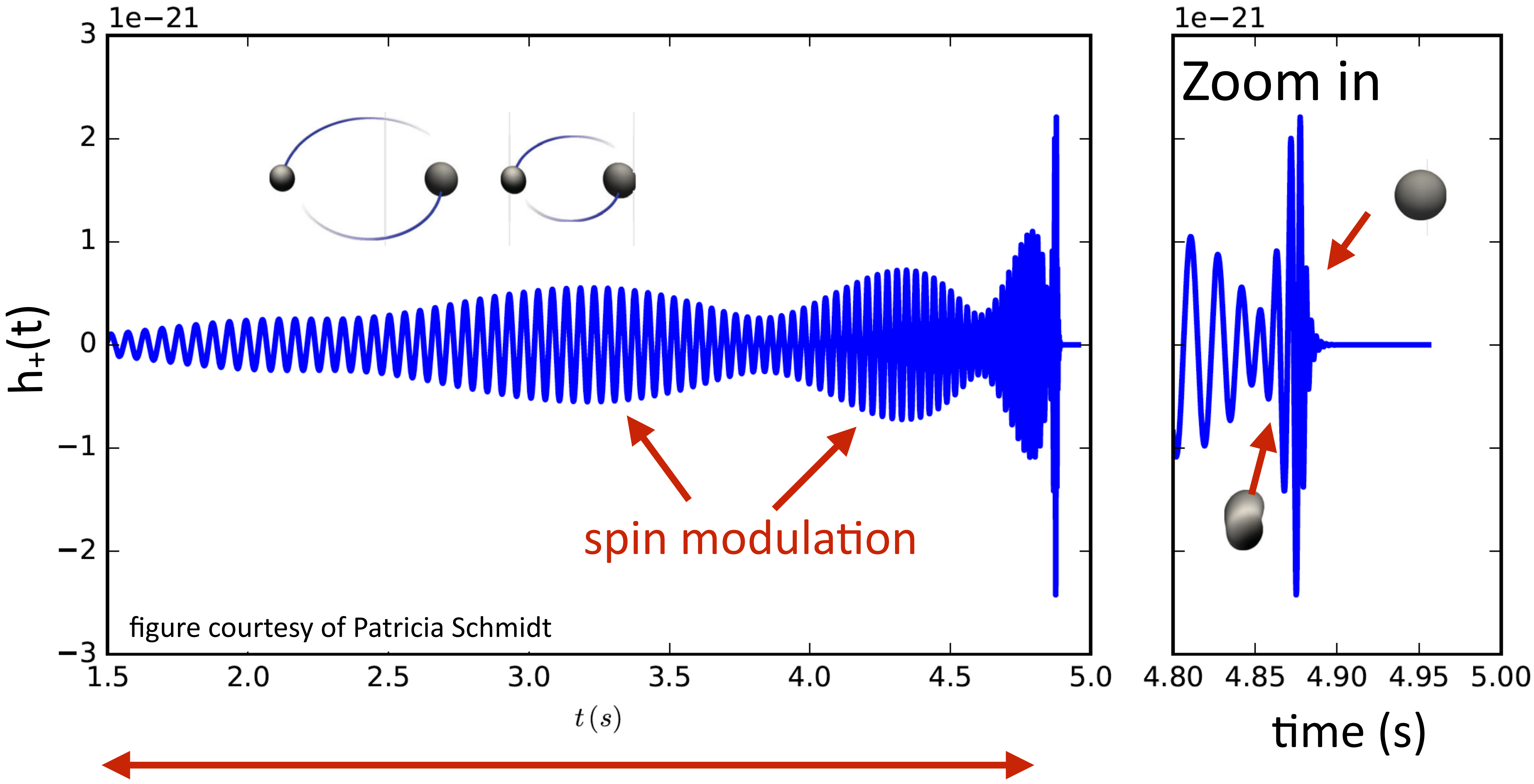
numerical relativity

quasi-normal modes

$$\boxed{1\mathrm{PN} \sim \frac{v^2}{c^2} \sim \frac{Gm}{rc^2} << 1}$$

[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

The GW waveform encodes source parameters



$\Phi_{\mathrm{GW}}(t)$ ⇒ chirp mass, reduced mass (1PN), spin-orbit (1.5PN), …

The GW chirp gives the progenitor masses and spins

$$
\begin{aligned}
a_1^i = &-\frac{Gm_2n_{12}^i}{r_{12}^2}\\
&+\frac{1}{c^2}\left\{\left[\frac{5G^2m_1m_2}{r_{12}^3}+\frac{4G^2m_2^2}{r_{12}^3}+\frac{Gm_2}{r_{12}^2}\left(\frac{3}{2}(n_{12}v_2)^2-v_1^2+4(v_1v_2)-2v_2^2\right)\right]n_{12}^i\right.\\
&\qquad\left.+\frac{Gm_2}{r_{12}^2}\left(4(n_{12}v_1)-3(n_{12}v_2)\right)v_{12}^i\right\}\\
&+\frac{1}{c^4}\left\{\left[-\frac{57G^3m_1^2m_2}{4r_{12}^4}-\frac{69G^3m_1m_2^2}{2r_{12}^4}-\frac{9G^3m_2^3}{r_{12}^4}\right.\right.\\
&\qquad+\frac{Gm_2}{r_{12}^2}\left(-\frac{15}{8}(n_{12}v_2)^4+\frac{3}{2}(n_{12}v_2)^2v_1^2-6(n_{12}v_2)^2(v_1v_2)-2(v_1v_2)^2+\frac{9}{2}(n_{12}\right.\\
&\qquad\qquad\left.+4(v_1v_2)v_2^2-2v_2^4\right)\\
&\qquad+\frac{G^2m_1m_2}{r_{12}^3}\left(\frac{39}{2}(n_{12}v_1)^2-39(n_{12}v_1)(n_{12}v_2)+\frac{17}{2}(n_{12}v_2)^2-\frac{15}{4}v_1^2-\frac{5}{2}(v_1v_2)+\right.\\
&\qquad\left.+\frac{G^2m_2^2}{r_{12}^3}\left(2(n_{12}v_1)^2-4(n_{12}v_1)(n_{12}v_2)-6(n_{12}v_2)^2-8(v_1v_2)+4v_2^2\right)\right]n_{12}^i\\
&\qquad+\left[\frac{G^2m_2^2}{r_{12}^3}\left(-2(n_{12}v_1)-2(n_{12}v_2)\right)+\frac{G^2m_1m_2}{r_{12}^3}\left(-\frac{63}{4}(n_{12}v_1)+\frac{55}{4}(n_{12}v_2)\right)\right.\\
&\qquad\quad+\frac{Gm_2}{r_{12}^2}\left(-6(n_{12}v_1)(n_{12}v_2)^2+\frac{9}{2}(n_{12}v_2)^3+(n_{12}v_2)v_1^2-4(n_{12}v_1)(v_1v_2)\right.\\
&\qquad\qquad\left.\left.\left.+4(n_{12}v_2)(v_1v_2)+4(n_{12}v_1)v_2^2-5(n_{12}v_2)v_2^2\right)\right]v_{12}^i\right\}\\
&+\frac{1}{c^5}\left\{\left[\frac{208G^3m_1m_2^2}{15r_{12}^4}(n_{12}v_{12})-\frac{24G^3m_1^2m_2}{5r_{12}^4}(n_{12}v_{12})+\frac{12G^2m_1m_2}{5r_{12}^3}(n_{12}v_{12})v_{12}^2\right]n_{12}^i\right.\\
&\qquad\left.+\left[\frac{8G^3m_1^2m_2}{5r_{12}^4}-\frac{32G^3m_1m_2^2}{5r_{12}^4}-\frac{4G^2m_1m_2}{5r_{12}^3}v_{12}^2\right]v_{12}^i\right\}\\
&+\frac{1}{c^6}\left\{\left[\frac{Gm_2}{r_{12}^2}\left(\frac{35}{16}(n_{12}v_2)^6-\frac{15}{8}(n_{12}v_2)^4v_1^2+\frac{15}{2}(n_{12}v_2)^4(v_1v_2)+3(n_{12}v_2)^2(v_1v_2)^2\right.\right.\right.\\
&\qquad\qquad-\frac{15}{2}(n_{12}v_2)^4v_2^2+\frac{3}{2}(n_{12}v_2)^2v_1^2v_2^2-12(n_{12}v_2)^2(v_1v_2)v_2^2-2(v_1v_2)^2v_2^2\\
&\qquad\qquad\left.+\frac{15}{2}(n_{12}v_2)^2v_2^4+4(v_1v_2)v_2^4-2v_2^6\right)\\
&\qquad+\frac{G^2m_1m_2}{r_{12}^3}\left(-\frac{171}{8}(n_{12}v_1)^4+\frac{171}{2}(n_{12}v_1)^3(n_{12}v_2)-\frac{723}{4}(n_{12}v_1)^2(n_{12}v_2)^2\right.\\
&\qquad\qquad+\frac{383}{2}(n_{12}v_1)(n_{12}v_2)^3-\frac{455}{8}(n_{12}v_2)^4+\frac{229}{4}(n_{12}v_1)^2v_1^2\\
&\qquad\qquad-\frac{205}{2}(n_{12}v_1)(n_{12}v_2)v_1^2+\frac{191}{4}(n_{12}v_2)^2v_1^2-\frac{91}{8}v_1^4-\frac{229}{2}(n_{12}v_1)^2v_1\\
&\qquad\qquad+244(n_{12}v_1)(n_{12}v_2)(v_1v_2)-\frac{225}{2}(n_{12}v_2)^2(v_1v_2)+\frac{91}{2}v_1^2(v_1v_2)\\
&\qquad\qquad-\frac{177}{4}(v_1v_2)^2+\frac{229}{4}(n_{12}v_1)^2v_2^2-\frac{283}{2}(n_{12}v_1)(n_{12}v_2)v_2^2\\
&\qquad\qquad\left.+\frac{259}{4}(n_{12}v_2)^2v_2^2-\frac{91}{4}v_1^2v_2^2+43(v_1v_2)v_2^2-\frac{81}{8}v_2^4\right)\\
&\qquad+\frac{G^2m_2^2}{r_{12}^3}\left(-6(n_{12}v_1)^2(n_{12}v_2)^2+12(n_{12}v_1)(n_{12}v_2)^3+6(n_{12}v_2)^4\right.\\
&\qquad\qquad+4(n_{12}v_1)(n_{12}v_2)(v_1v_2)+12(n_{12}v_2)^2(v_1v_2)+4(v_1v_2)^2\\
&\qquad\qquad\left.-4(n_{12}v_1)(n_{12}v_2)v_2^2-12(n_{12}v_2)^2v_2^2-8(v_1v_2)v_2^2+4v_2^4\right)\\
&\qquad+\frac{G^3m_2^3}{r_{12}^4}\left(-(n_{12}v_1)^2+2(n_{12}v_1)(n_{12}v_2)+\frac{43}{2}(n_{12}v_2)^2+18(v_1v_2)-9v_2^2\right)\\
&\qquad+\frac{G^3m_1m_2^2}{r_{12}^4}\left(\frac{415}{8}(n_{12}v_1)^2-\frac{375}{4}(n_{12}v_1)(n_{12}v_2)+\frac{1113}{8}(n_{12}v_2)^2-\frac{615}{64}(n_{12}v_{12})^2\pi^2\right.\\
&\qquad\qquad\left.+18v_1^2+\frac{123}{64}\pi^2v_{12}^2+33(v_1v_2)-\frac{33}{2}v_2^2\right)
\end{aligned}
$$

$$
\begin{aligned}
&+\frac{G^3m_1^2m_2}{r_{12}^4}\left(-\frac{45887}{168}(n_{12}v_1)^2+\frac{24025}{42}(n_{12}v_1)(n_{12}v_2)-\frac{10469}{42}(n_{12}v_2)^2+\frac{48197}{840}v_1^2\right.\\
&\qquad\left.-\frac{36227}{420}(v_1v_2)+\frac{36227}{840}v_2^2+110(n_{12}v_{12})^2\ln\left(\frac{r_{12}}{r'_1}\right)-22v_{12}^2\ln\left(\frac{r_{12}}{r'_1}\right)\right)\\
&+\frac{16G^4m_2^4}{r_{12}^5}+\frac{G^4m_1^2m_2^2}{r_{12}^5}\left(175-\frac{41}{16}\pi^2\right)+\frac{G^4m_1^3m_2}{r_{12}^5}\left(-\frac{3187}{1260}+\frac{44}{3}\ln\left(\frac{r_{12}}{r'_1}\right)\right)\\
&\left.+\frac{G^4m_1m_2^3}{r_{12}^5}\left(\frac{110741}{630}-\frac{41}{16}\pi^2-\frac{44}{3}\ln\left(\frac{r_{12}}{r'_2}\right)\right)\right]n_{12}^i\\
&+\left[\frac{Gm_2}{r_{12}^2}\left(\frac{15}{2}(n_{12}v_1)(n_{12}v_2)^4-\frac{45}{8}(n_{12}v_2)^5-\frac{3}{2}(n_{12}v_2)^3v_1^2+6(n_{12}v_1)(n_{12}v_2)^2(v_1v_2)\right.\right.\\
&\qquad-6(n_{12}v_2)^3(v_1v_2)-2(n_{12}v_2)(v_1v_2)^2-12(n_{12}v_1)(n_{12}v_2)^2v_2^2+12(n_{12}v_2)^3v_2^2\\
&\qquad+(n_{12}v_2)v_1^2v_2^2-4(n_{12}v_1)(v_1v_2)v_2^2+8(n_{12}v_2)(v_1v_2)v_2^2+4(n_{12}v_1)v_2^4\\
&\qquad\left.-7(n_{12}v_2)v_2^4\right)\\
&\quad+\frac{G^2m_2^2}{r_{12}^3}\left(-2(n_{12}v_1)^2(n_{12}v_2)+8(n_{12}v_1)(n_{12}v_2)^2+2(n_{12}v_2)^3+2(n_{12}v_1)(v_1v_2)\right.\\
&\qquad\qquad\left.+4(n_{12}v_2)(v_1v_2)-2(n_{12}v_1)v_2^2-4(n_{12}v_2)v_2^2\right)\\
&\quad+\frac{G^2m_1m_2}{r_{12}^3}\left(-\frac{243}{4}(n_{12}v_1)^3+\frac{565}{4}(n_{12}v_1)^2(n_{12}v_2)-\frac{269}{4}(n_{12}v_1)(n_{12}v_2)^2\right.\\
&\qquad\qquad-\frac{95}{12}(n_{12}v_2)^3+\frac{207}{8}(n_{12}v_1)v_1^2-\frac{137}{8}(n_{12}v_2)v_1^2-36(n_{12}v_1)(v_1v_2)\\
&\qquad\qquad\left.+\frac{27}{4}(n_{12}v_2)(v_1v_2)+\frac{81}{8}(n_{12}v_1)v_2^2+\frac{83}{8}(n_{12}v_2)v_2^2\right)\\
&\quad+\frac{G^3m_2^3}{r_{12}^4}\left(4(n_{12}v_1)+5(n_{12}v_2)\right)\\
&\quad+\frac{G^3m_1m_2^2}{r_{12}^4}\left(-\frac{307}{8}(n_{12}v_1)+\frac{479}{8}(n_{12}v_2)+\frac{123}{32}(n_{12}v_{12})\pi^2\right)\\
&\quad\left.\left.+\frac{G^3m_1^2m_2}{r_{12}^4}\left(\frac{31397}{420}(n_{12}v_1)-\frac{36227}{420}(n_{12}v_2)-44(n_{12}v_{12})\ln\left(\frac{r_{12}}{r'_1}\right)\right)\right]v_{12}^i\right\}
\end{aligned}
$$

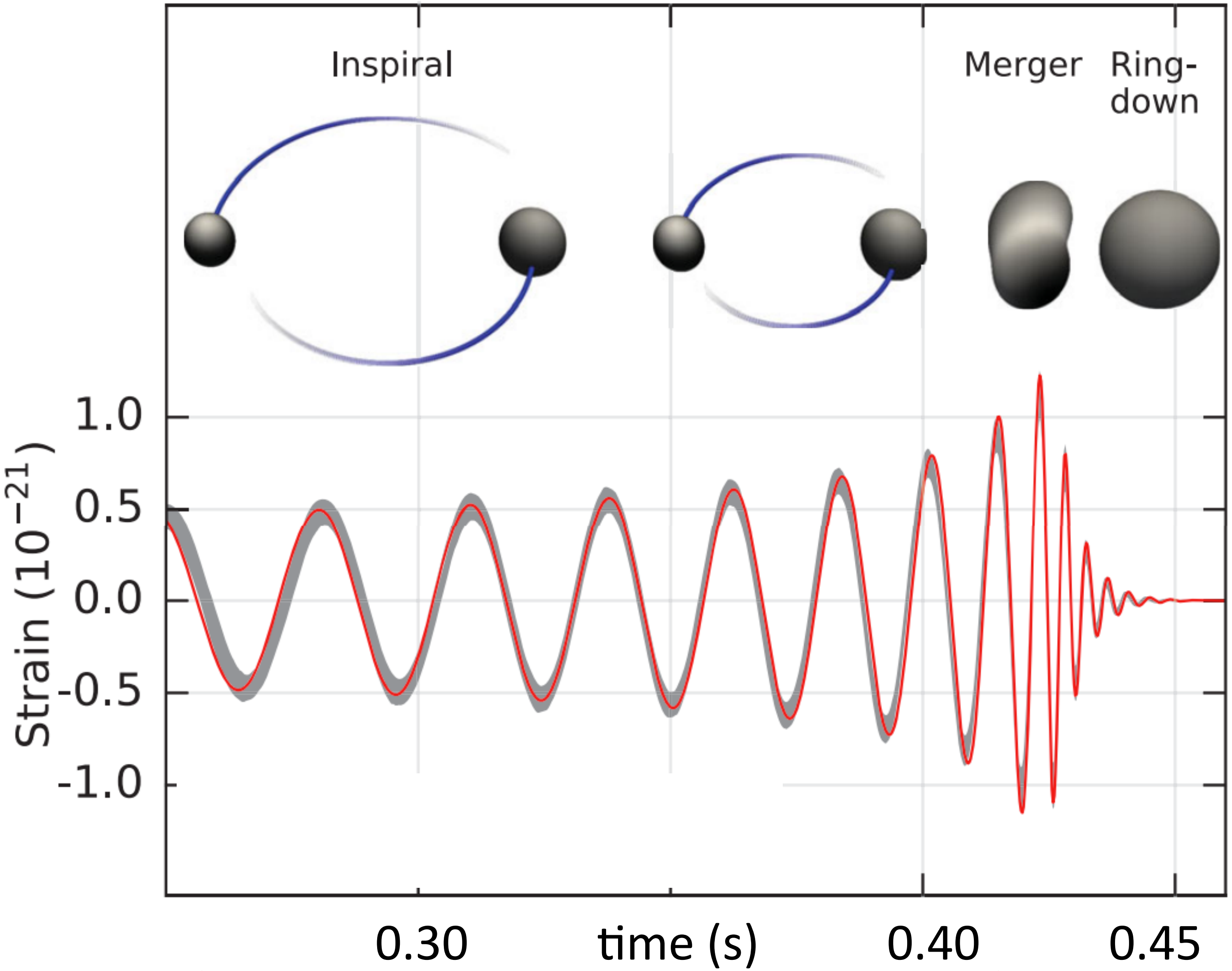
$$
\begin{aligned}
&+\frac{1}{c^7}\left\{\left[\frac{G^4m_1^3m_2}{r_{12}^5}\left(\frac{3992}{105}(n_{12}v_1)-\frac{4328}{105}(n_{12}v_2)\right)\right.\right.\\
&\qquad+\frac{G^4m_1^2m_2^2}{r_{12}^6}\left(-\frac{13576}{105}(n_{12}v_1)+\frac{2872}{21}(n_{12}v_2)\right)-\frac{3172}{21}\frac{G^4m_1m_2^3}{r_{12}^6}(n_{12}v_{12})\\
&\qquad+\frac{G^3m_1^2m_2}{r_{12}^4}\left(48(n_{12}v_1)^3-\frac{696}{5}(n_{12}v_1)^2(n_{12}v_2)+\frac{744}{5}(n_{12}v_1)(n_{12}v_2)^2-\frac{288}{5}(n_{12}v_2)^3\right.\\
&\qquad\qquad-\frac{4888}{105}(n_{12}v_1)v_1^2+\frac{5056}{105}(n_{12}v_2)v_1^2+\frac{2056}{21}(n_{12}v_1)(v_1v_2)\\
&\qquad\qquad\left.-\frac{2224}{21}(n_{12}v_2)(v_1v_2)-\frac{1028}{21}(n_{12}v_1)v_2^2+\frac{5812}{105}(n_{12}v_2)v_2^2\right)\\
&\qquad+\frac{G^3m_1m_2^2}{r_{12}^4}\left(-\frac{582}{5}(n_{12}v_1)^3+\frac{1746}{5}(n_{12}v_1)^2(n_{12}v_2)-\frac{1954}{5}(n_{12}v_1)(n_{12}v_2)^2\right.
\end{aligned}
$$

$$
\begin{aligned}
&\qquad\qquad+158(n_{12}v_2)^3+\frac{3568}{105}(n_{12}v_{12})v_1^2-\frac{2864}{35}(n_{12}v_1)(v_1v_2)\\
&\qquad\qquad\left.+\frac{10048}{105}(n_{12}v_2)(v_1v_2)+\frac{1432}{35}(n_{12}v_1)v_2^2-\frac{5752}{105}(n_{12}v_2)v_2^2\right)\\
&\qquad+\frac{G^2m_1m_2}{r_{12}^3}\left(-56(n_{12}v_{12})^5+60(n_{12}v_1)^3v_{12}^2-180(n_{12}v_1)^2(n_{12}v_2)v_{12}^2\right.\\
&\qquad\qquad+174(n_{12}v_1)(n_{12}v_2)^2v_{12}^2-54(n_{12}v_2)^3v_{12}^2-\frac{246}{35}(n_{12}v_{12})v_1^4\\
&\qquad\qquad+\frac{1068}{35}(n_{12}v_1)v_1^2(v_1v_2)-\frac{984}{35}(n_{12}v_2)v_1^2(v_1v_2)-\frac{1068}{35}(n_{12}v_1)(v_1v_2)^2\\
&\qquad\qquad+\frac{180}{7}(n_{12}v_2)(v_1v_2)^2-\frac{534}{35}(n_{12}v_1)v_1^2v_2^2+\frac{90}{7}(n_{12}v_2)v_1^2v_2^2\\
&\qquad\qquad+\frac{984}{35}(n_{12}v_1)(v_1v_2)v_2^2-\frac{732}{35}(n_{12}v_2)(v_1v_2)v_2^2-\frac{204}{35}(n_{12}v_1)v_2^4\\
&\qquad\qquad\left.\left.+\frac{24}{7}(n_{12}v_2)v_2^4\right)\right]n_{12}^i\\
&\quad+\left[-\frac{184}{21}\frac{G^4m_1^3m_2}{r_{12}^5}+\frac{6224}{105}\frac{G^4m_1^2m_2^2}{r_{12}^6}+\frac{6388}{105}\frac{G^4m_1m_2^3}{r_{12}^6}\right.\\
&\qquad+\frac{G^3m_1^2m_2}{r_{12}^4}\left(\frac{52}{15}(n_{12}v_1)^2-\frac{56}{15}(n_{12}v_1)(n_{12}v_2)-\frac{44}{15}(n_{12}v_2)^2-\frac{132}{35}v_1^2+\frac{152}{35}(v_1v_2)\right.\\
&\qquad\qquad\left.-\frac{48}{35}v_2^2\right)\\
&\qquad+\frac{G^3m_1m_2^2}{r_{12}^4}\left(\frac{454}{15}(n_{12}v_1)^2-\frac{372}{5}(n_{12}v_1)(n_{12}v_2)+\frac{854}{15}(n_{12}v_2)^2-\frac{152}{21}v_1^2\right.\\
&\qquad\qquad\left.+\frac{2864}{105}(v_1v_2)-\frac{1768}{105}v_2^2\right)\\
&\qquad+\frac{G^2m_1m_2}{r_{12}^3}\left(60(n_{12}v_{12})^4-\frac{348}{5}(n_{12}v_1)^2v_{12}^2+\frac{684}{5}(n_{12}v_1)(n_{12}v_2)v_{12}^2\right.\\
&\qquad\qquad-66(n_{12}v_2)^2v_{12}^2+\frac{334}{35}v_1^4-\frac{1336}{35}v_1^2(v_1v_2)+\frac{1308}{35}(v_1v_2)^2+\frac{654}{35}v_1^2v_2^2\\
&\qquad\qquad\left.\left.\left.-\frac{1252}{35}(v_1v_2)v_2^2+\frac{292}{35}v_2^4\right)\right]v_{12}^i\right\}\\
&+\mathcal{O}\left(\frac{1}{c^8}\right).
\end{aligned}
$$

[Nissanke et al. 2005]

[Blanchet 2015; see also Nissanke et al. 2005, Nissanke 2006, Blanchet, Faye, Nissanke 2005, MacDonald, Nissanke, Pfeiffer 2011]

Decades of theoretical effort in source modelling



post-Newtonian

numerical relativity

quasi-normal modes

$$\boxed{1\mathrm{PN} \sim \frac{v^2}{c^2} \sim \frac{Gm}{rc^2} << 1}$$

[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

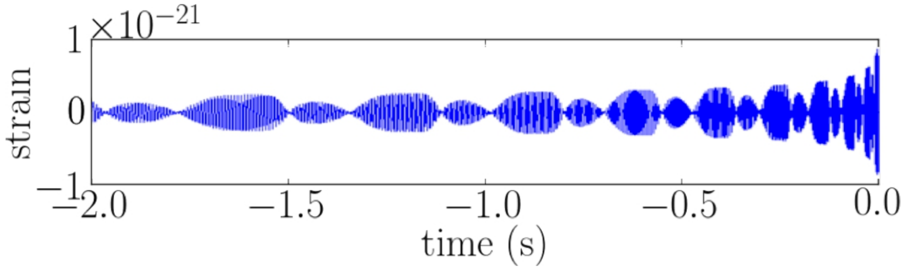
Extract source information from GWs

$$h_+(t) = \frac{A[\overset{\substack{\text{frequency}\\ \uparrow}}{\mathcal{M}\, f(t)}]}{\underset{\swarrow\ \text{distance}}{D}}\,(1+\cos^2 \underset{\substack{\downarrow\\ \text{inclination angle}}}{\iota})\cos \underset{\substack{\downarrow\\ \text{GW Phase}}}{\Phi_{\mathrm{GW}}}(t)$$

h(t): 9-15 parameters

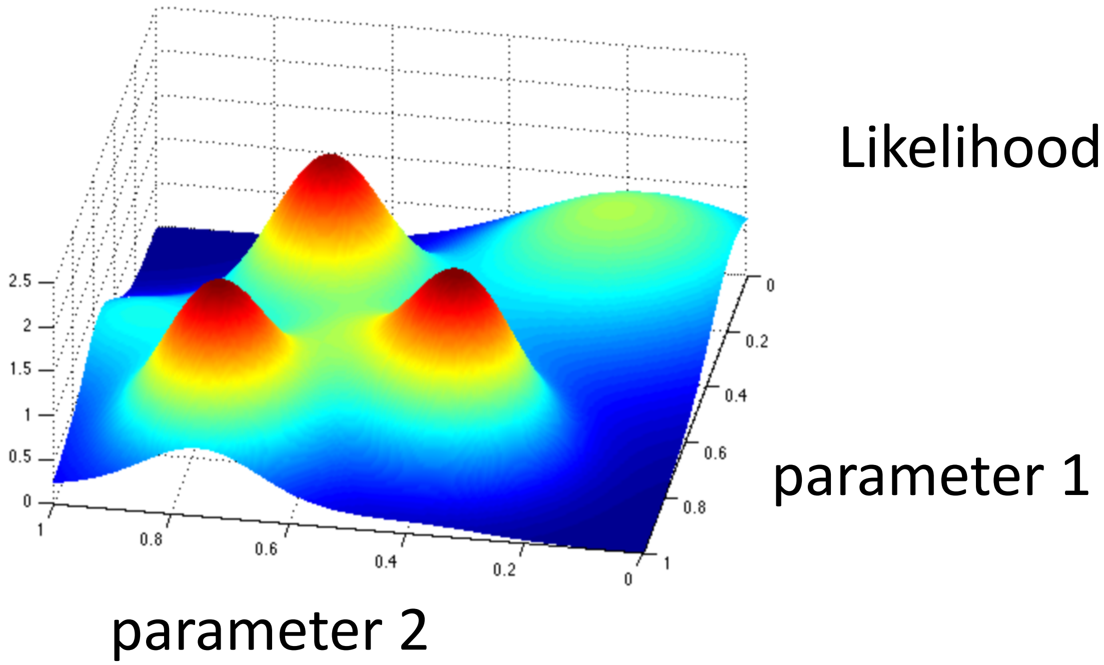
+ Redshifted Masses
+ Redshifted Spins
+ Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Model h(t)



Detector output

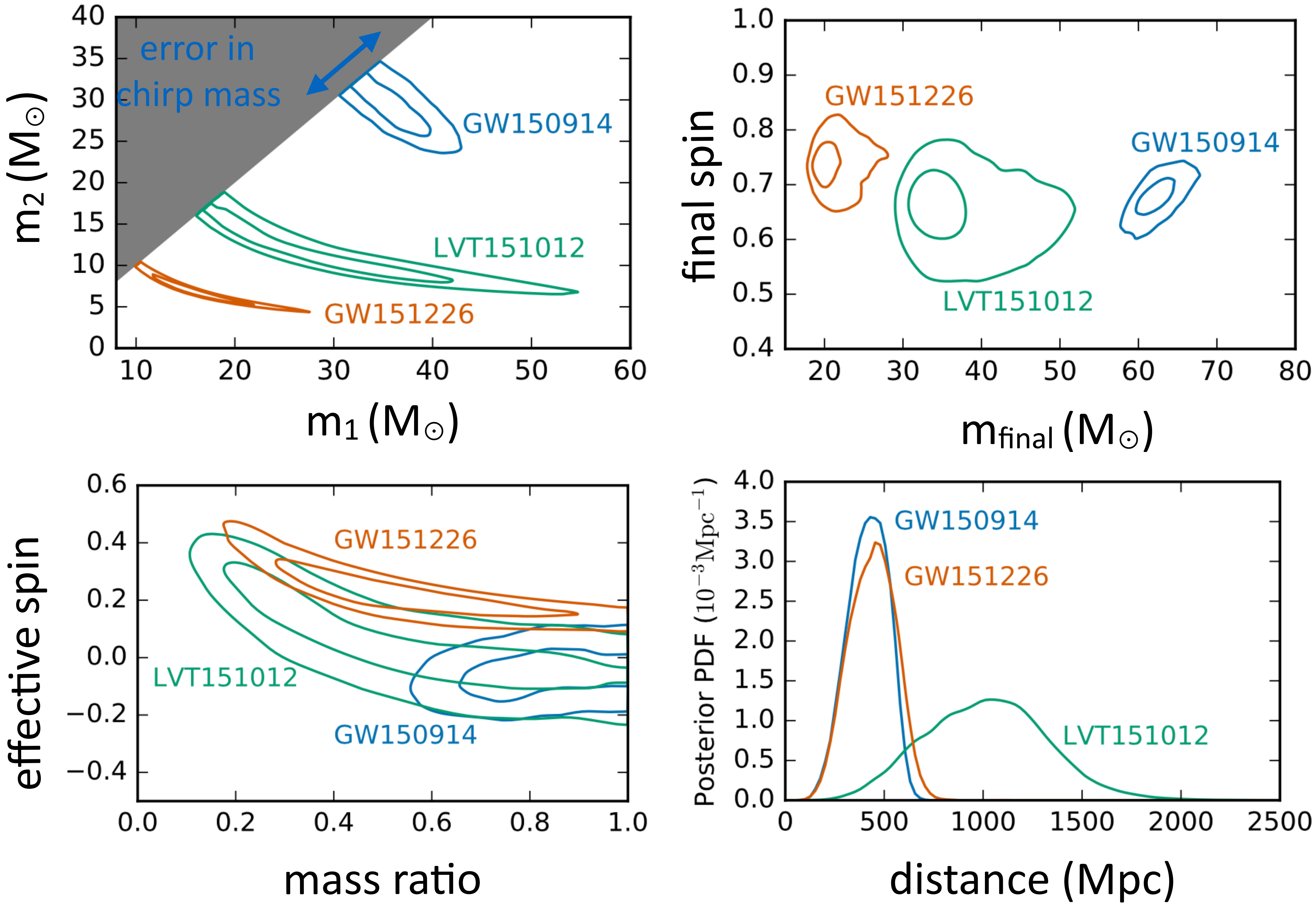
Explicitly map out: $p(\boldsymbol{\theta}|s) \propto p(\boldsymbol{\theta})\mathcal{L}_{\mathrm{total}}(s|\boldsymbol{\theta})$



using Bayesian Markov Chain Monte Carlo and Nested Sampling Techniques

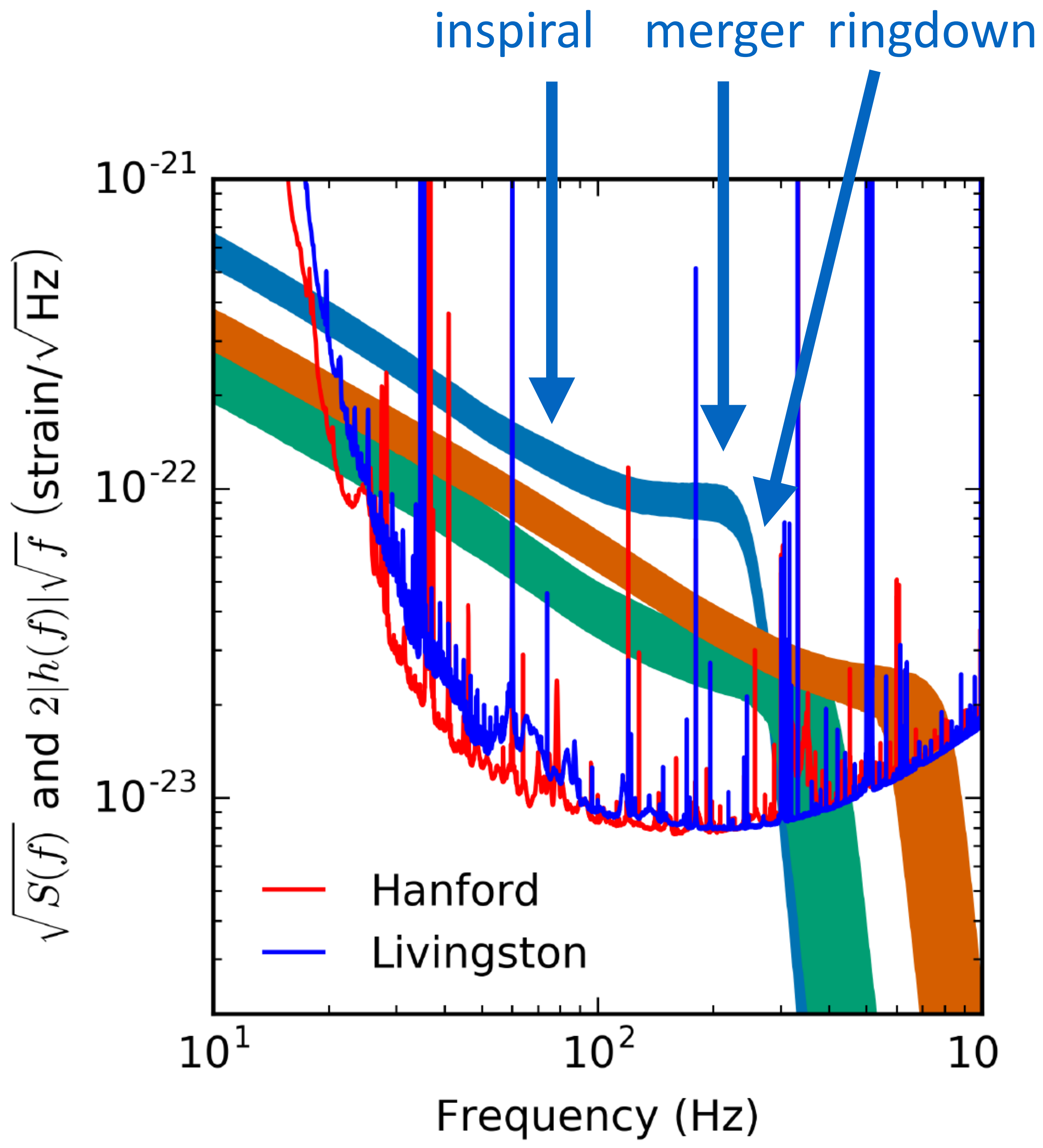
[see LVC, arXiv: 1602.03840, PRL 116, 241102, 2016]

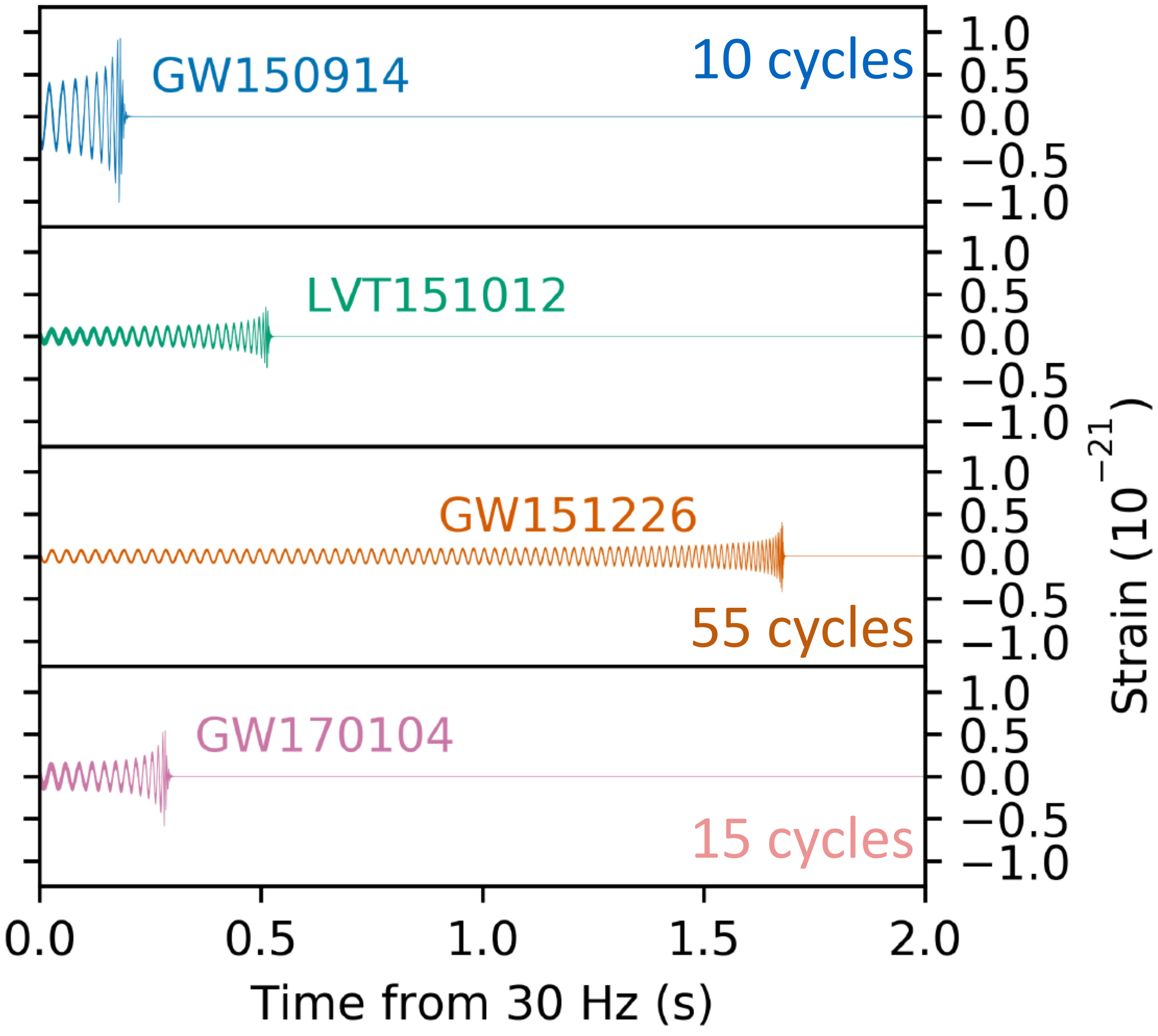
Large degeneracies when retrieving BH parameters: errors are several 10s of %



[LVC, arXiv:1606.04856, PRX 6, 041015, 2016]

… errors depend on what epoch of waveform is in the detector noise bucket!

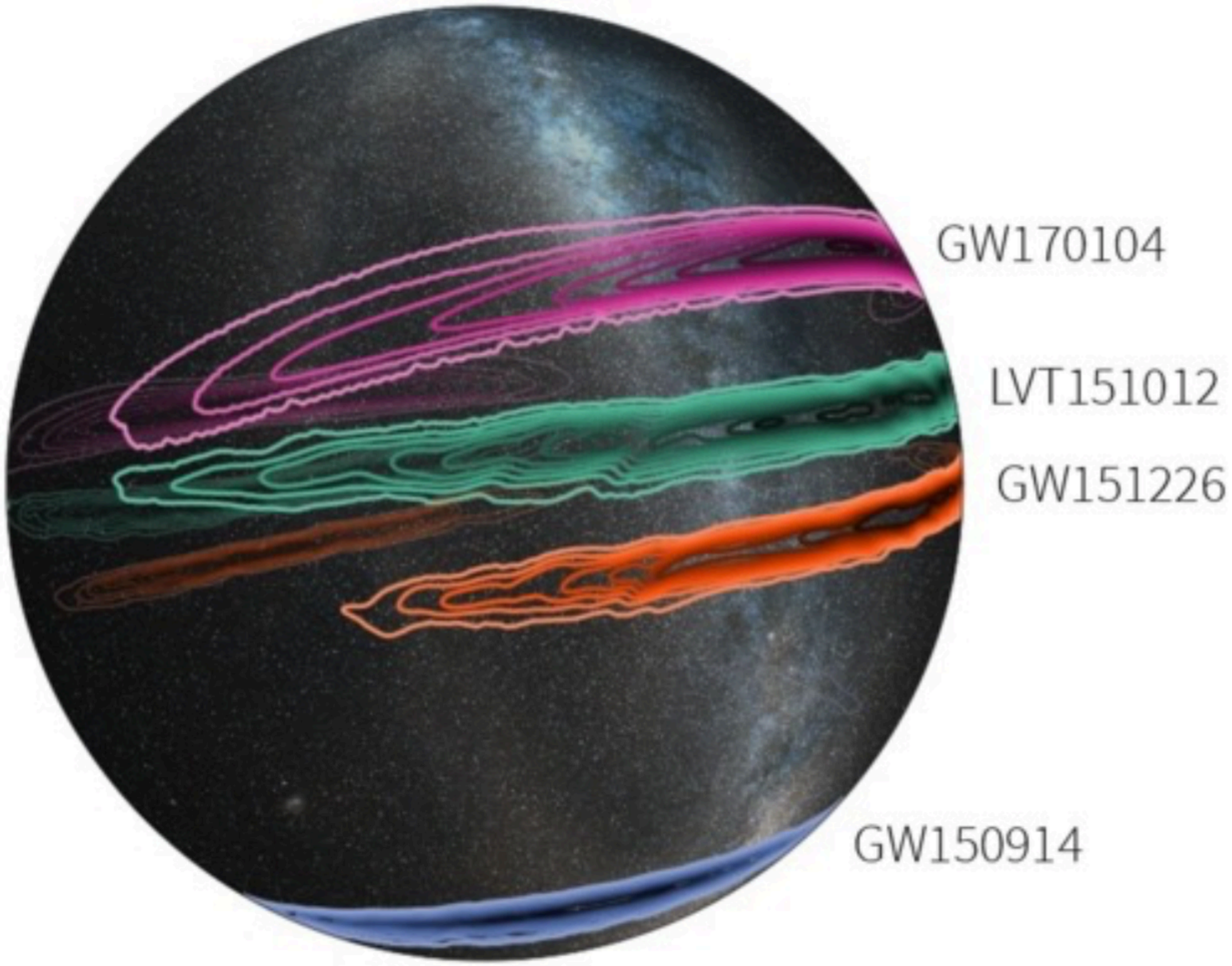




[LVC, arXiv:1606.04856, PRX 6, 041015, 2016, and LVC, Phys. Rev. Lett. 118, 221101, 2017]

Part II:
EM follow-up in practice

How well can we localise the source on the sky?



1200 sq. deg. (90% c.r.)

1600 sq. deg. (90% c.r.)

1000 [850] sq. deg.
(90% c.r.)

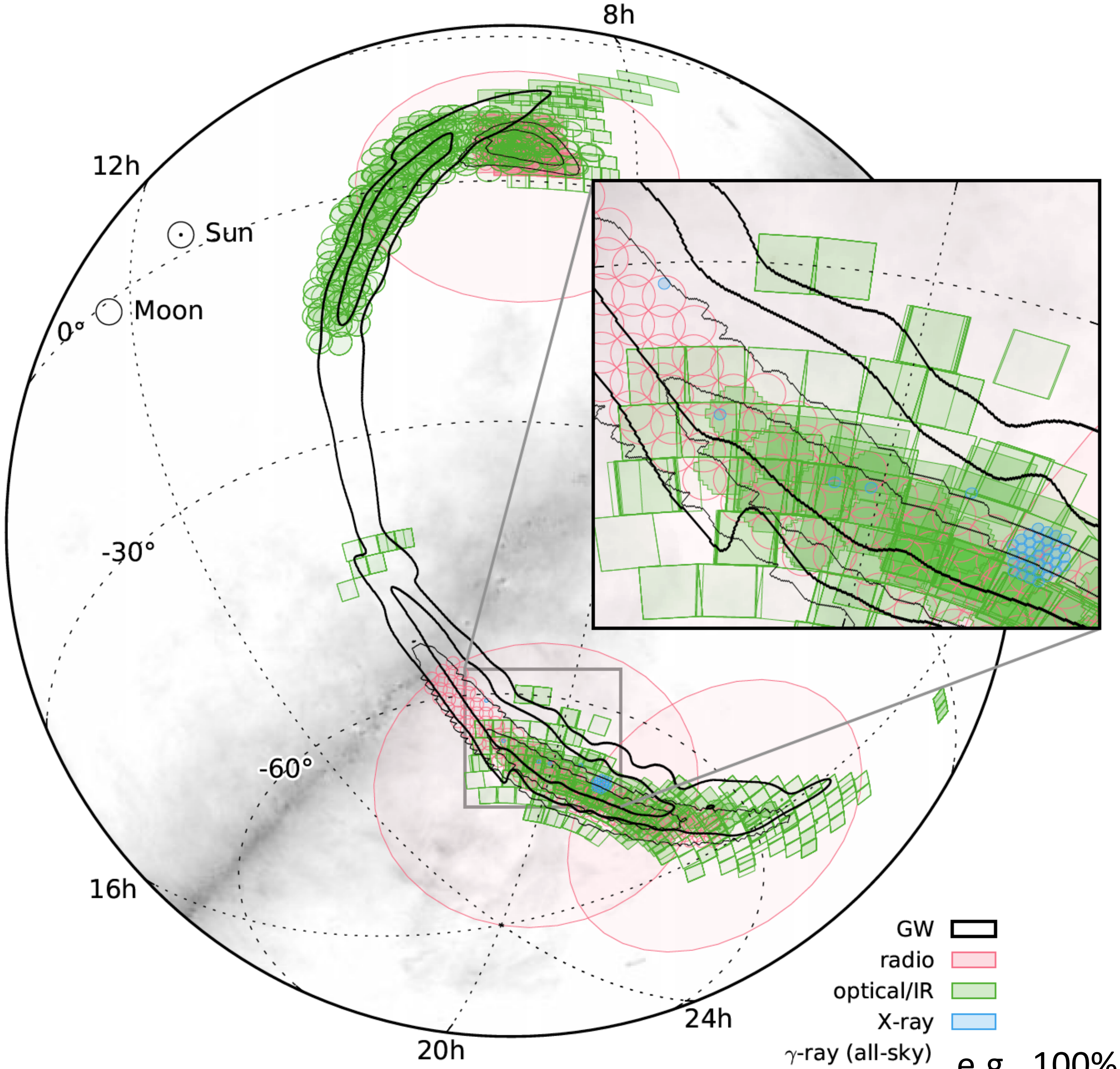
590 [230] sq. deg. (90% c.r.)

[Image credit: LIGO/L. Singer/A. Messinger]

10^5-10^7 galaxies in these volumes

[LVC, arXiv:1606.04856, PRX 6, 041015, 2016]

2015: EM follow-up by 24 observatories for GW150914



e.g., 100% to 10^{-7} ergs $cm^{-2}s^{-1}$

19 orders of magnitude in frequency space

Also, high-energy neutrino search with IceCube/Antares (+/- 500s)

[LVC+EM observers, APJL, 826, 1, L13, 2016;
Antares+Icecube+LVC, Phys Rev D 93, 122010, 2016, Phys. Rev. D 96, 022005, 2017]

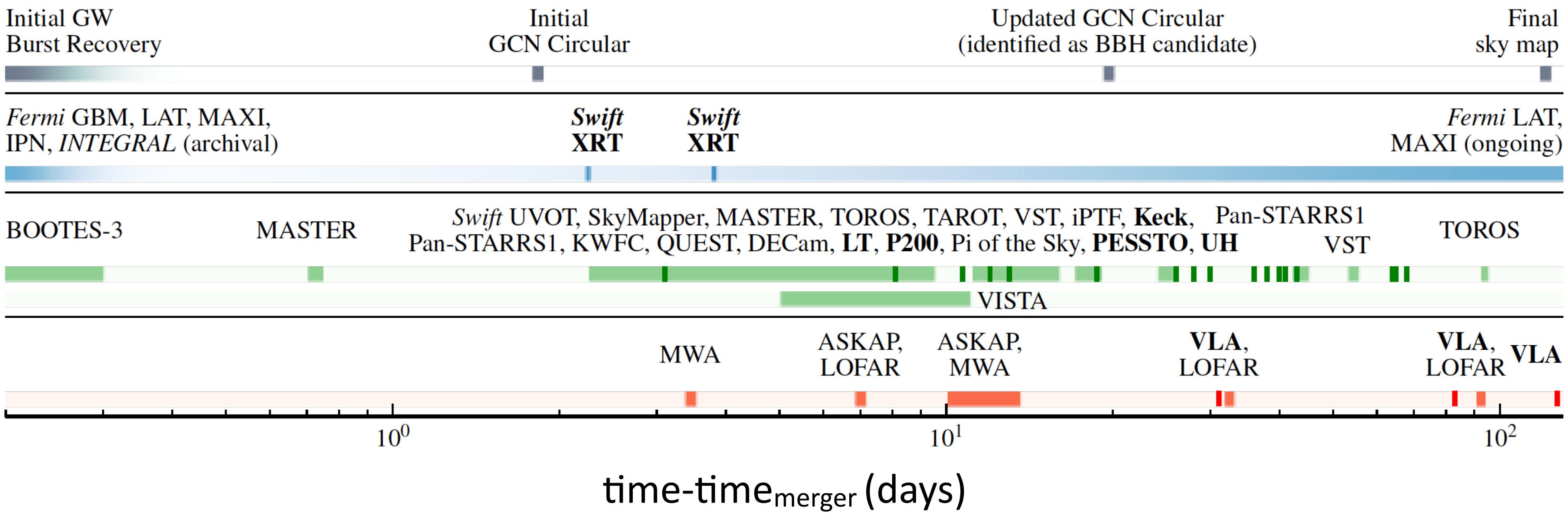
Challenge 1: time of alert & nature of source/distance information/depth

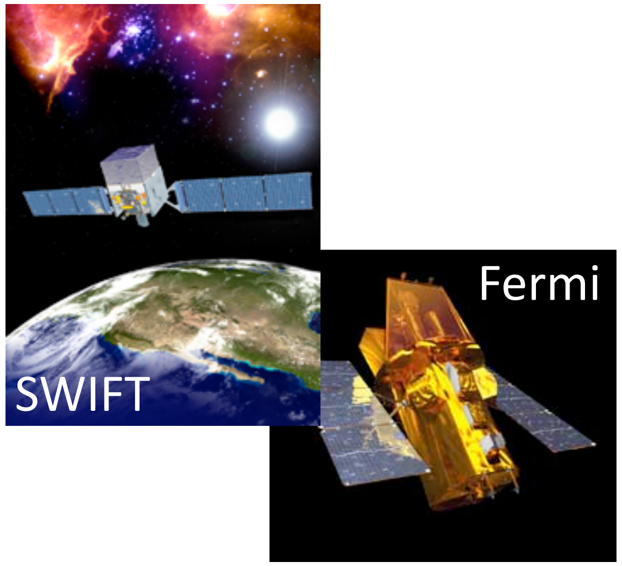
[LVC, APJL, 826, 1, L13, 2016]

HIGH ENERGY

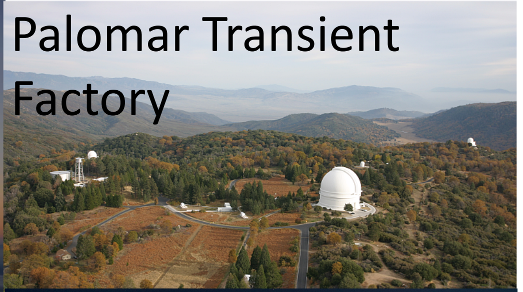
OPTICAL/NEAR-IR

RADIO





HIGH ENERGY

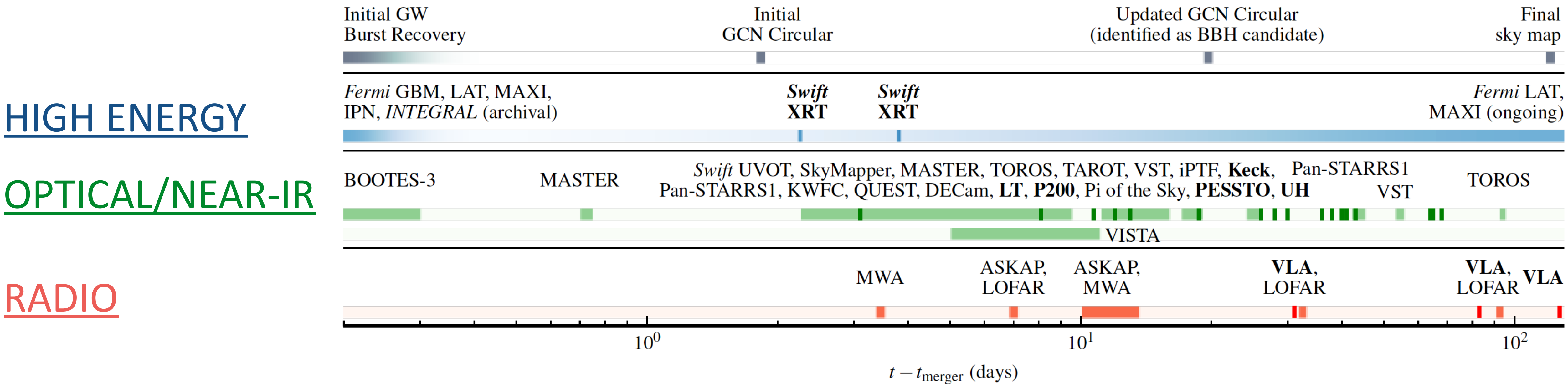


OPTICAL/NEAR-IR

RADIO

Challenge 1: time of alert & nature of source/distance information/depth

[LVC, APJL, 826, 1, L13, 2016]



Today: GW170104 was sent out within 7 hours of the detection, with information about the distance/source nature!

[LVC, Phys. Rev. Lett. 118, 221101, 2017; see EM tiling strategy papers with depth e.g.,Salafia et al. arXiv:1704.05851. Ghosh et al. 2016, Leong et al. 2016, Bhalerao et al. 2016, …]

Challenge 2: Many other events bubbling, burping, or exploding in GW sky errors

GW150914: tens of other transients and variables

- Supernova type Ia and II
- Active Galactic Nucleii
- a few dwarf nova
- …

GW distance and redshift are critical

[GW150914 - e.g., Connaughton et al. arXiv:1602.03920; Savchenko et al. 2016 ApJL 820, 36; Morokuma et al.arXiv:1605.03216; Fermi--LAT collaboration APJL, 823,2; Lipunov et al. arXiv:1605.01607; Soares-Santos et al., arXiv:1602.04198; Smartt et al. arXiv:160204156S; Evans et al. MNRAS 460, L40; Annis et al. arXiv:1602.04199; Kasliwal et al. arXiv:1602.08764 ,…]

Challenge 2: Many other events bubbling, burping, or exploding in GW sky errors

GW150914: tens of other transients and variables

- Supernova type Ia and II
- Active Galactic Nucleii
- a few dwarf nova
- …

No reported real-time observed EM counterpart …
..bar de facto, FERMI GBM: sub-threshold event between 1 keV and 10 MeV of 1.8×10^{49} ergs/s, 0.4 s after the GW event, FAP of 0.0022, lasting 1s.

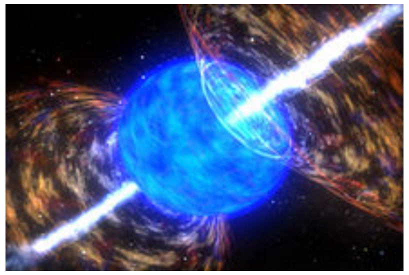
[Connaughton et al. 2016]

Challenge 3: Speculative EM counterparts to BBH

BUT: No candidates reported by Integral & independent second analysis of FERMI results are in tension.

[Savchenko et al. 2016, Grenier et al. 2016]

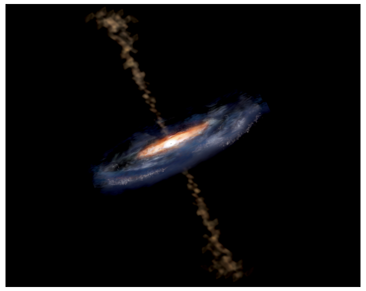
e.g., arXiv in the week following the announcement:
Short Gamma-Ray Bursts from the Merger of Two Black Hole
Perna et al. 2016
Electromagnetic Counterparts to Black Hole Mergers Detected by LIGO
Loeb 2016
Electromagnetic Afterglows Associated with Gamma-Ray Emission Coincident with Binary Black Hole Merger Event GW150914
Yamazaki et al. 2016
Mergers of Charged Black Holes: Gravitational Wave Events, Short Gamma-Ray Bursts, and Fast Radio Bursts
Zhang 2016
Implication of the association between GBM transient 150914 and LIGO Gravitational Wave event GW150914
Li et al. 2016
Ultrafast Outflows from Black Hole Mergers with a Mini-Disk
Murase et al. 2016
Rapid and Bright Stellar-mass Binary Black Hole Mergers in Active Galactic Nuclei
Bartos et al. 2015
Ultrahigh Energy Cosmic Rays and Black Hole Mergers
Kotera and Silk, 2016

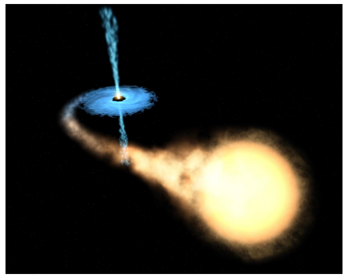


'collapsar-like'

BBH embedded

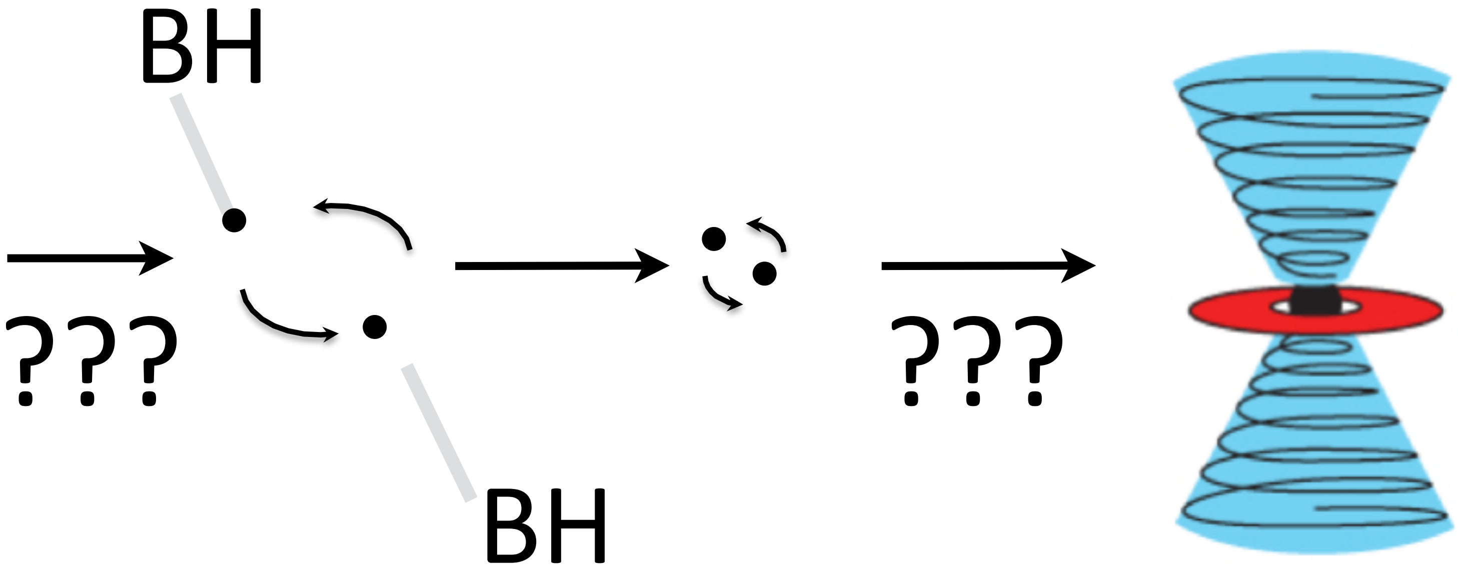
in AGN disk ?





ultrafast mini-disk

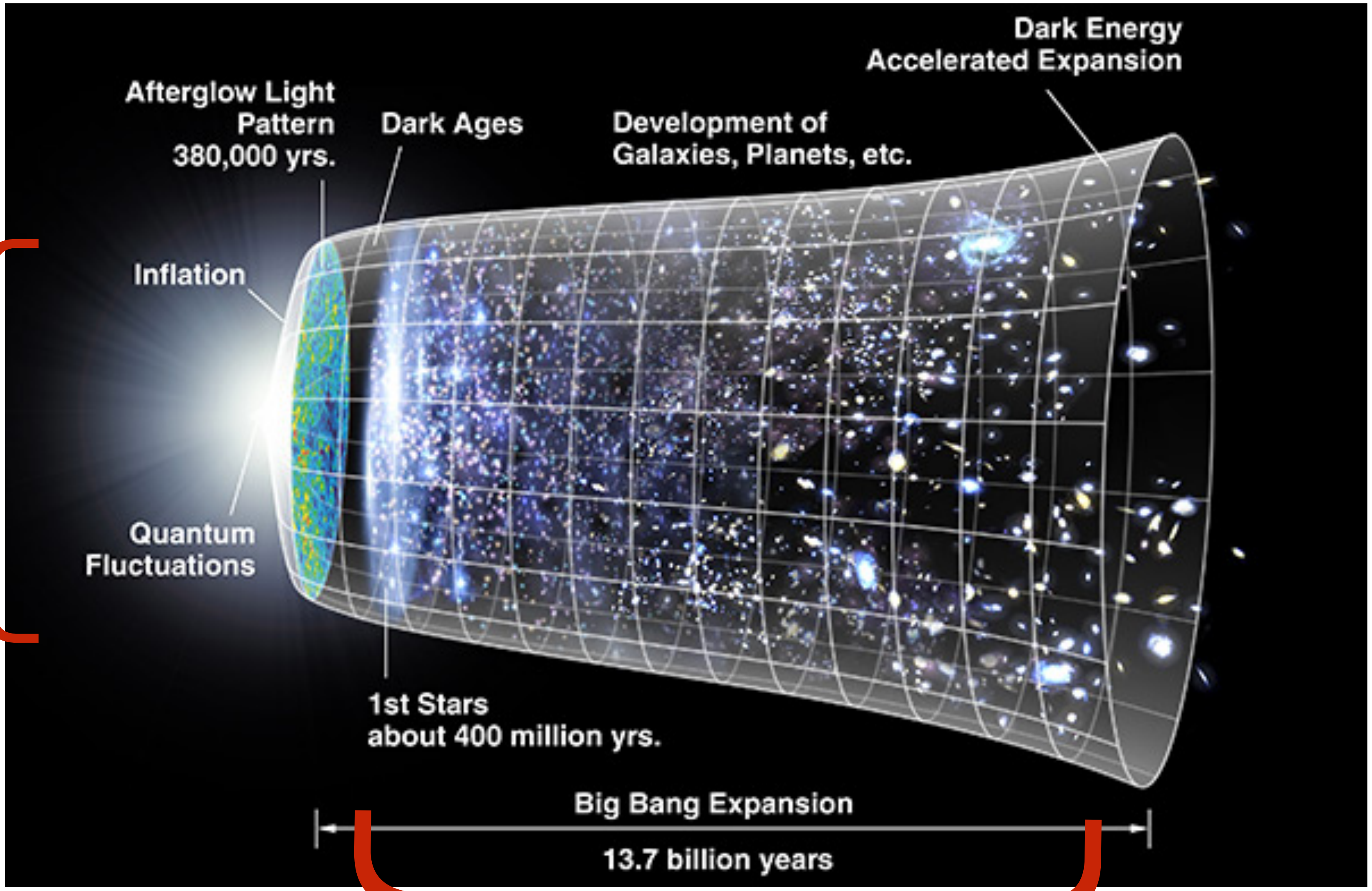
from third body ?



Part III:
How to connect GW measurements to astrophysics with EM counterparts?

Challenge: How, where and when do BBHs form?

Primordial BHs from density fluctuations in early Universe



Pop III: first massive stars (1% of stars in Universe)
Pop II/I: classic field binary evolution (90%)
Pop II/I: rapid rotation (10%)
Pop II/I: dynamical formation in globular clusters (0.1%)
Exotic: e.g. single star core splitting

Weak massive stellar winds, low metallicity environments

[LVC, ApJL 818, L22, 2016]

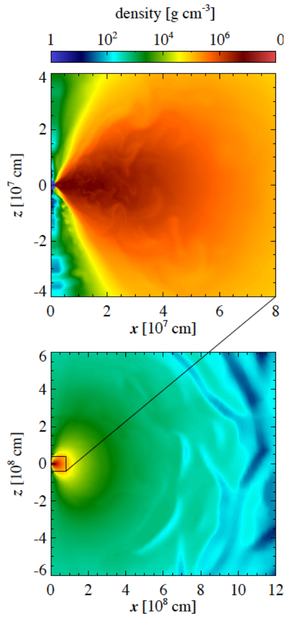
Two Types of Matter Outflows from NS binary mergers

1. Tidal Tails + Disk Winds

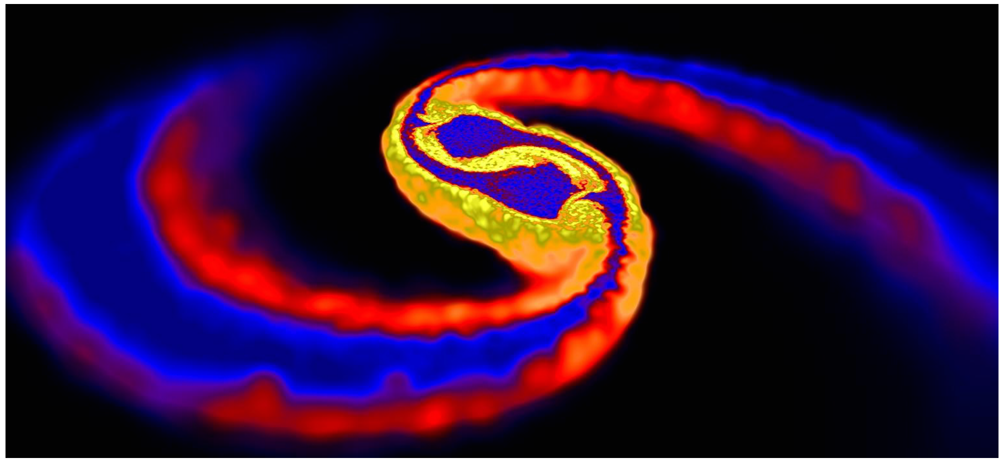
$M_{ej} \approx 10^{-4}$ - 0.01 $M_\odot$

$E \approx 10^{49}$- 10^{50} ergs

$v \approx 0.1$-$0.3c$



[Fernandez & Metzger 2013]



[Rosswog 2012, 2013, 2015]

2. Ultra-relativistic Jet

$M_{ej} \approx 10^{-6}$ $M_\odot$

$E \approx 10^{49}$- 10^{51} ergs

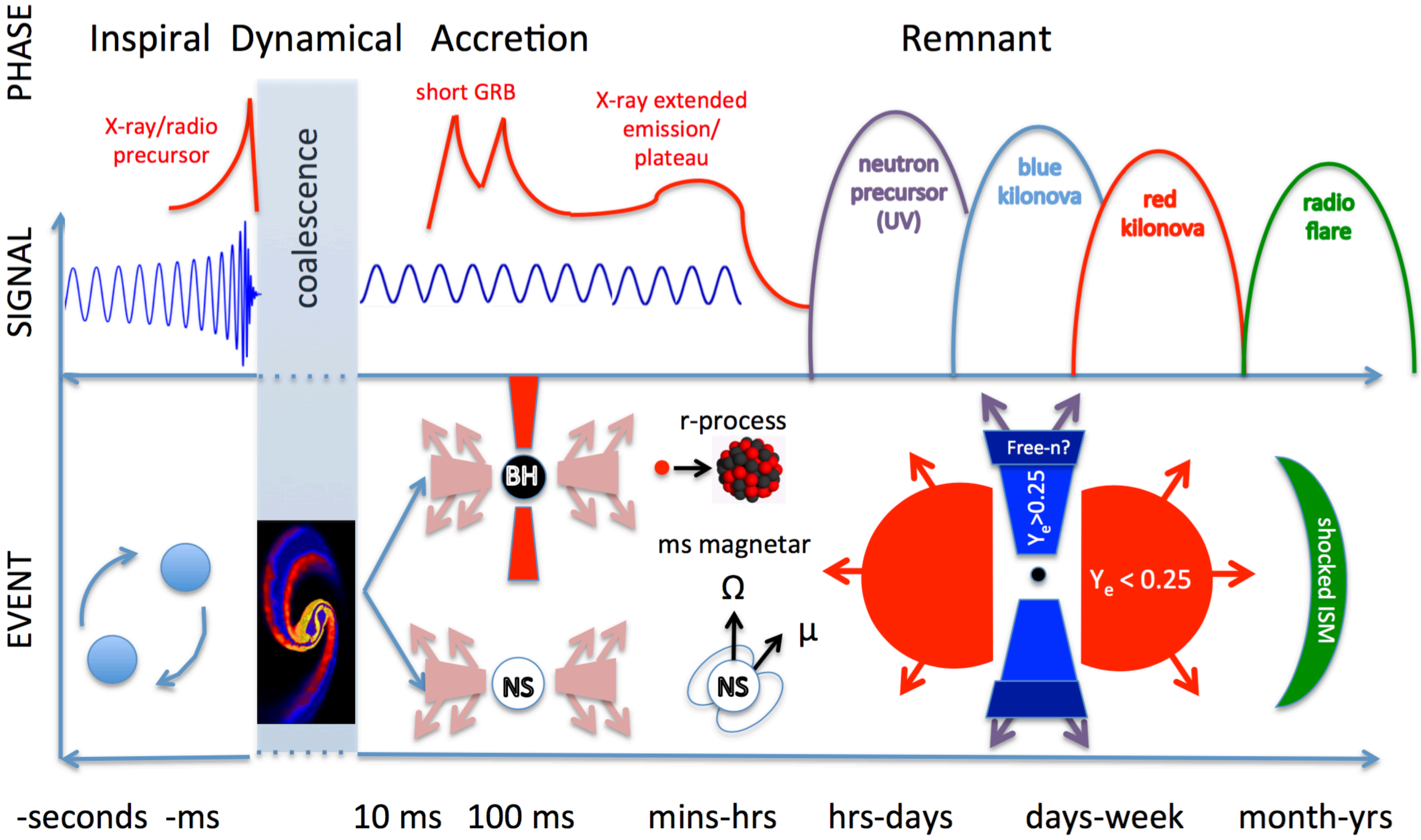
$\Gamma \approx 100$

[Rezzolla et al. 2011]

[see e.g., Rezzolla et al. 2010, 2014, Palenzuela et al, 2010, 2011, Hotokezaka et al., 2012, 2014, Rosswog et al. 2012, Piran et al. 2013, Bauswein et al. 2013, Foucart et al. 2014, Nagakura et al., 2014, Bernuzzi et al. 2013, Kyutoku et al. 2014, Ciolfi and Siegel 2014,15, Fernandez et al. 2014, Paschalidis et al. 2015, Ruiz et al. 2016, Radice et al. 2016, Siegel et al. 2017 …]

(cf. Supernova: 10^{51} ergs)

Two types of outflows ⇒ Plethora of EM counterparts



[Fernandez and Metzger, 1512.05435, and references therein]

[see also Tsang et al. 2011, Metzger et al., Siegel et al. 2016,17, Gottlieb et al., 2017]

Next step: combine & interpret GW + EM

h(t): 9-16 parameters

- Redshifted Masses (several to tens %)
- Redshifted Spins (tens of %)
- NS radii (tens of %)
- Geometric properties: (tens of %)
  - Inclination angle
  - Source Position
  - Luminosity distance

$F_\lambda(t)$: 5-10 parameters

- Energetics and beaming
- R-process nucleosynthesis
- Mass ejecta and velocity
- Environment
- Redshift, Accurate Position (1”)
- Stellar populations
- Magnetic field strength
- Previous binary evolution & mass loss

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Strong signal binary: Characterisation

New field: break degeneracies to measure properties of BHs and NSs

$h(t)$: 9-16 parameters

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- Redshift, Accurate Position (1")
- Stellar populations
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- Previous binary evolution & mass loss

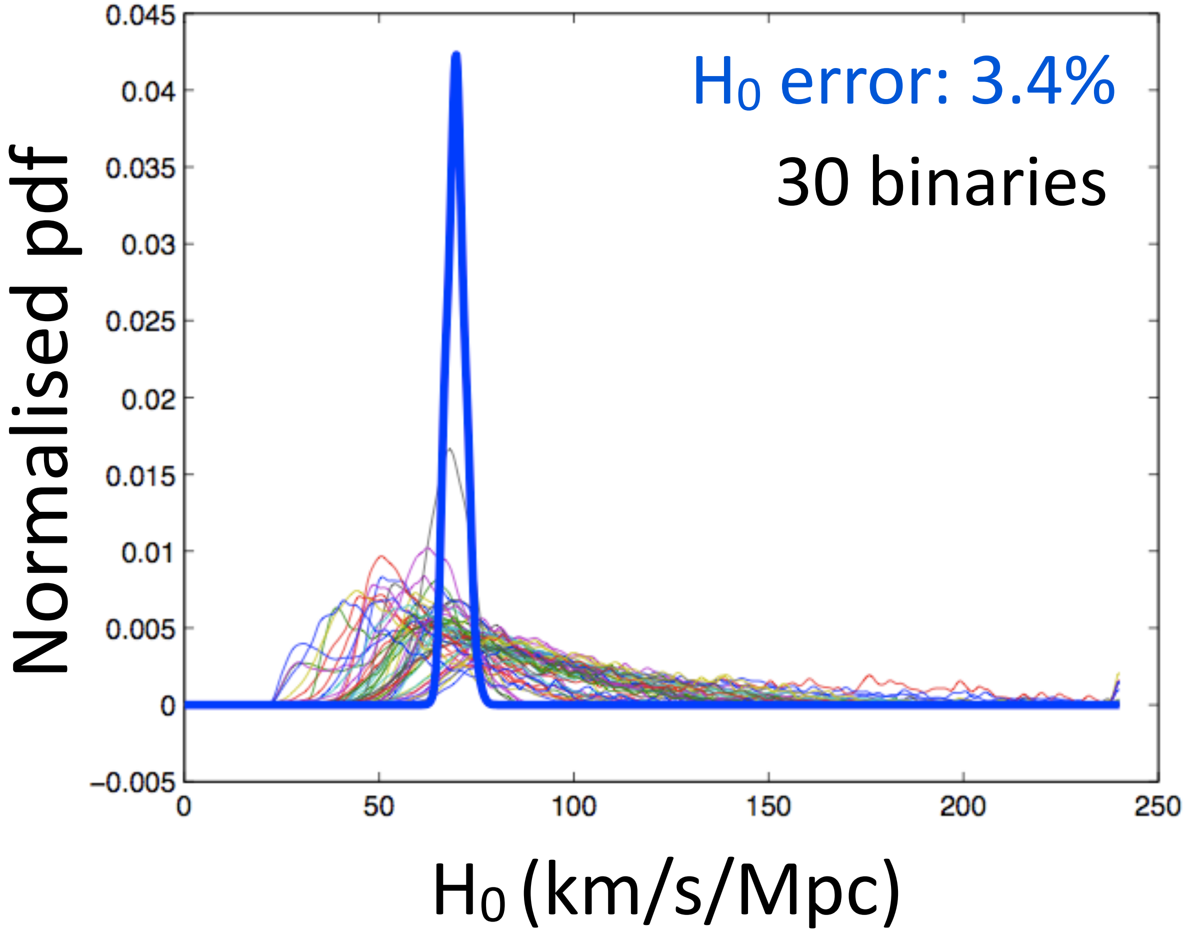
Strong signal binary: Characterisation

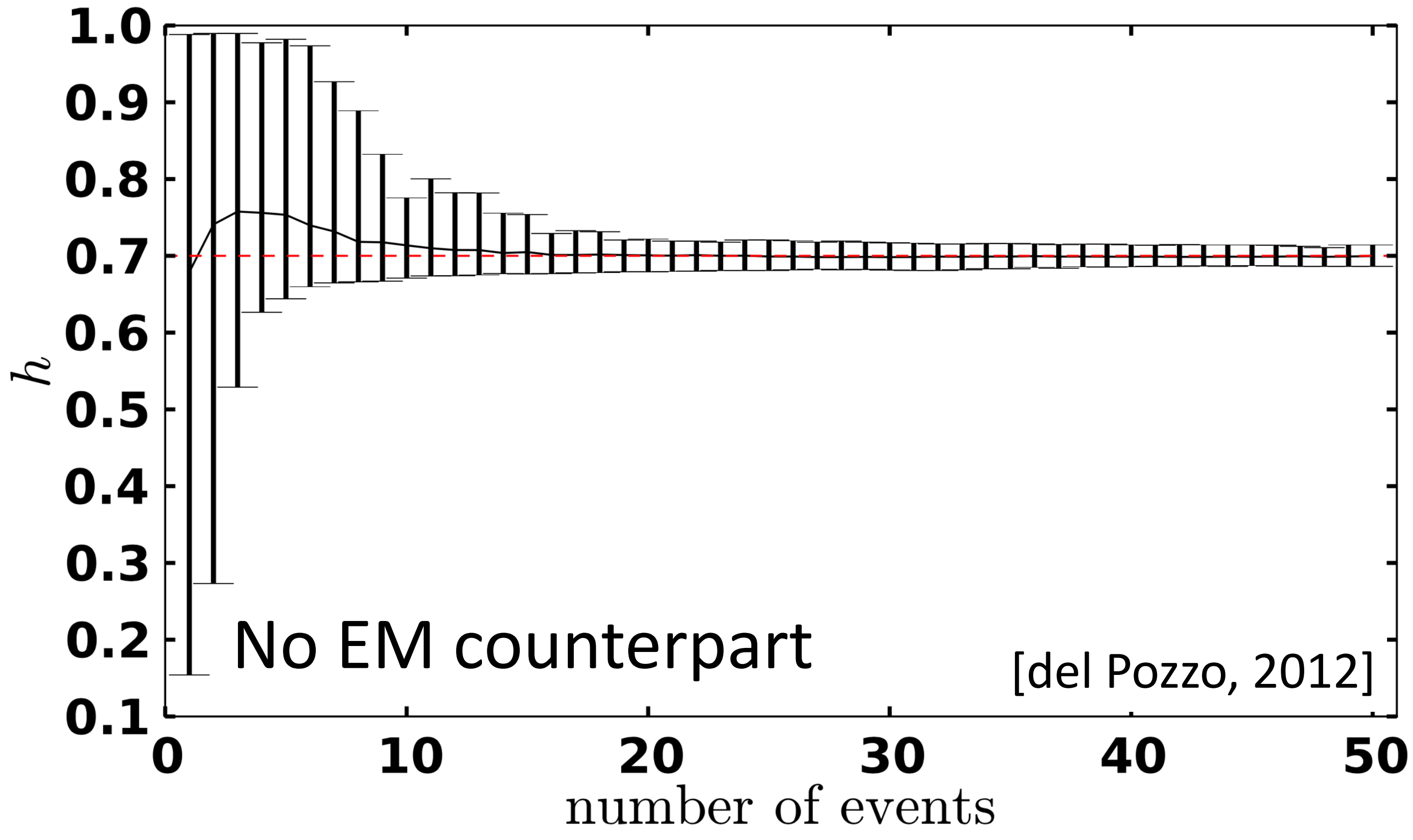
Population: Demographics, ecology and census

GW+EM enable a few % error in Hubble constant … importance of populations !!!

[see Schutz 1986, Dalal et al. 2006,
Sathyaprakash et al. 2010, Cutler et al. 2009,
Messenger et al. 2012, Taylor et al. 2012, …]

[Nissanke et al., 2010,13]



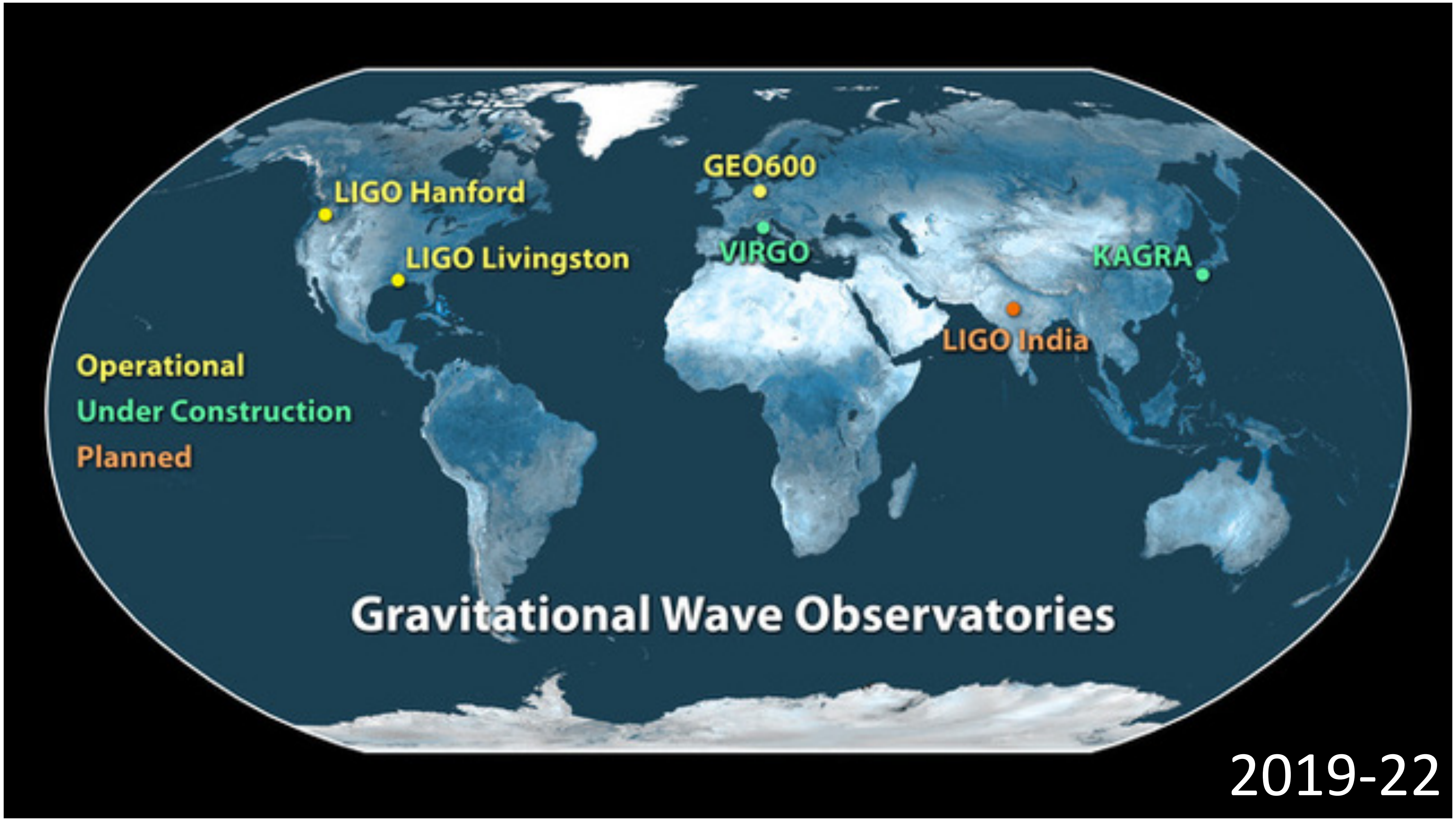


[del Pozzo, 2012]

Similar reasoning applies detecting BH memory, testing GR and neutron star equation of states …

[e.g., Lasky et al. 2016, Yunes et al. 2013, Meidam et al. 2014, Lackay & Wade 2014, Agathos et al. 2014,15, Yagi et al. 2017]

Expanding the GW detector network for EM follow up in 2020s

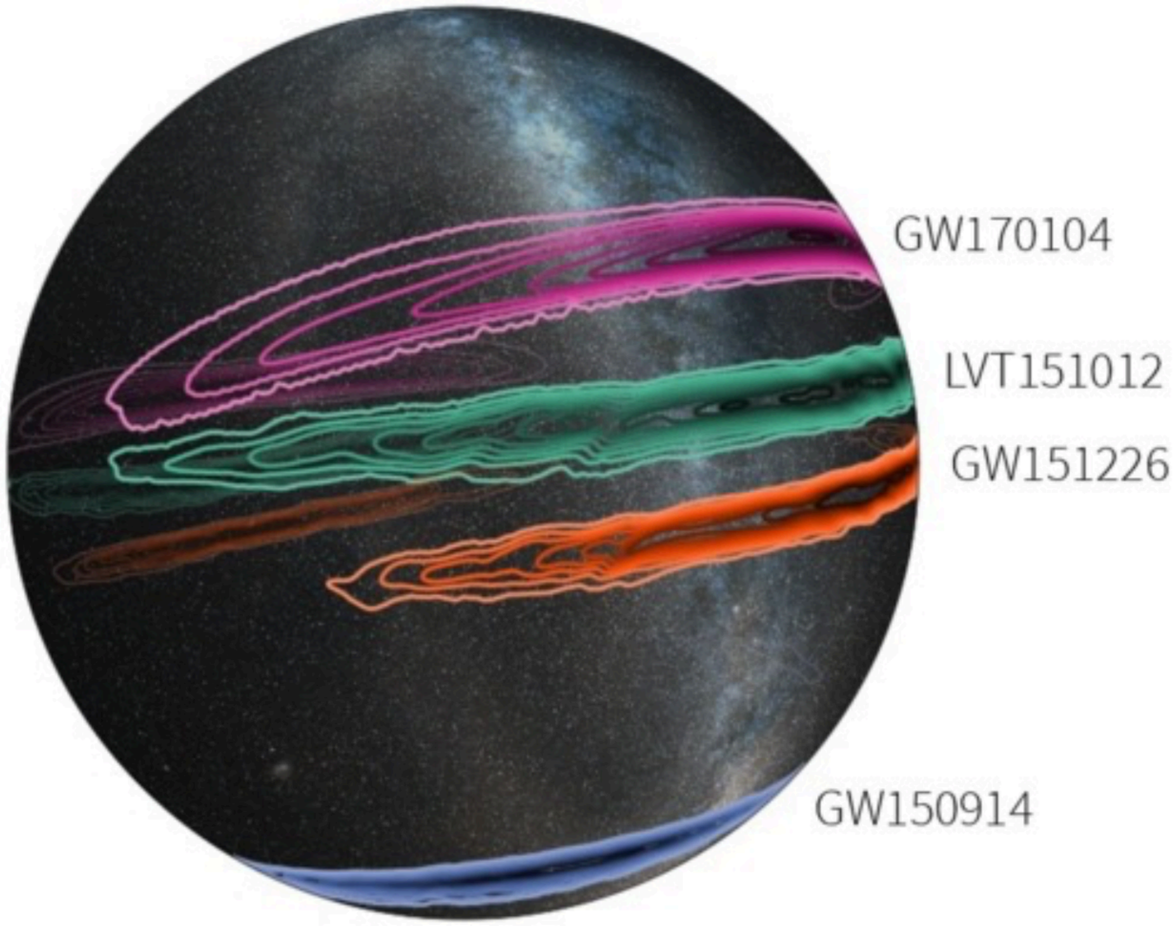


O2 Science Run: 11/16 - 08/17 (81 days as of 23rd June)
August 1st 2017: Virgo joined O2 science run!

[see roadmap in LSC&Virgo collaboration—arXiv:1304.0670]

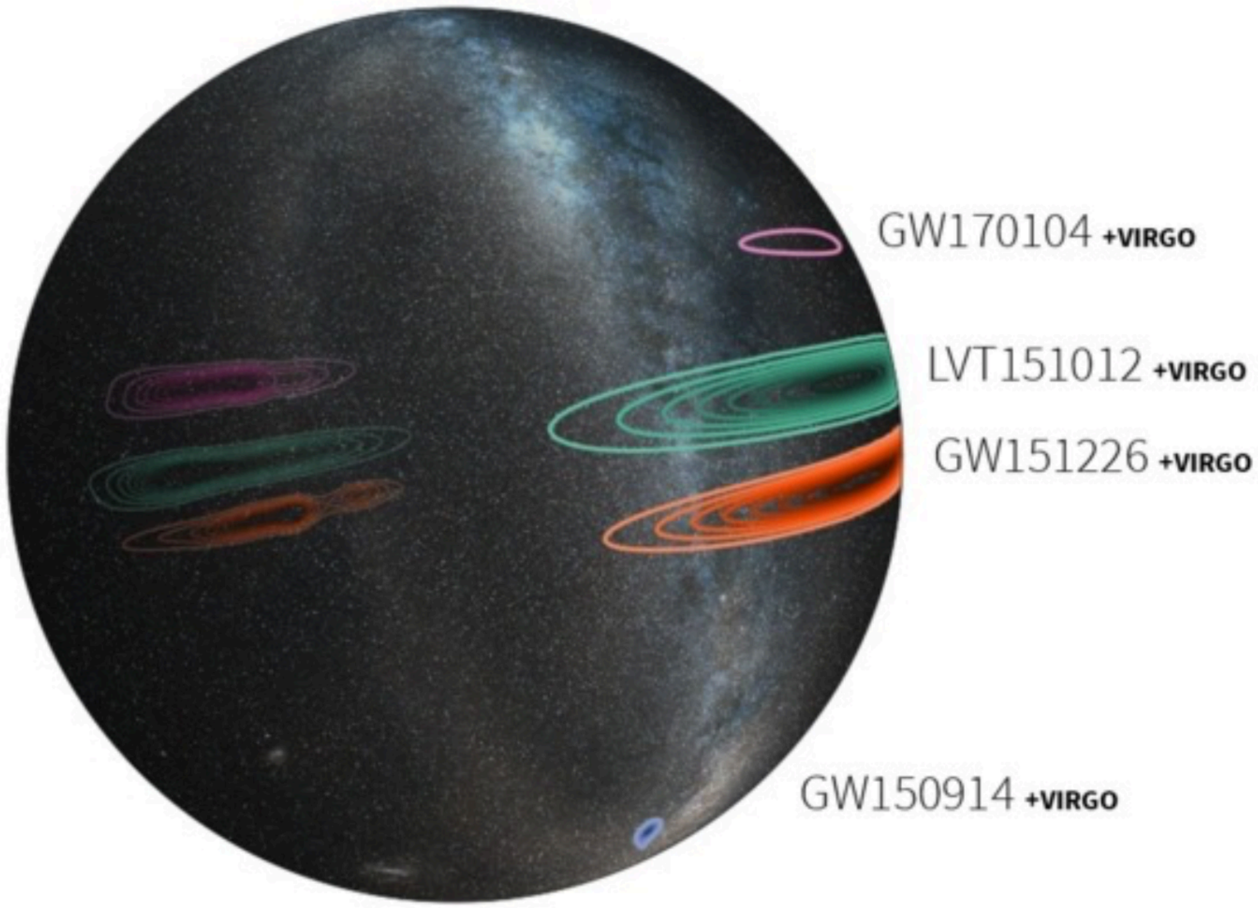
Immediate future: expanding & increasing the sensitivity of the worldwide GW network

2015-2017



[Image credit: LIGO/L. Singer/A. Messinger]

2017-2018+



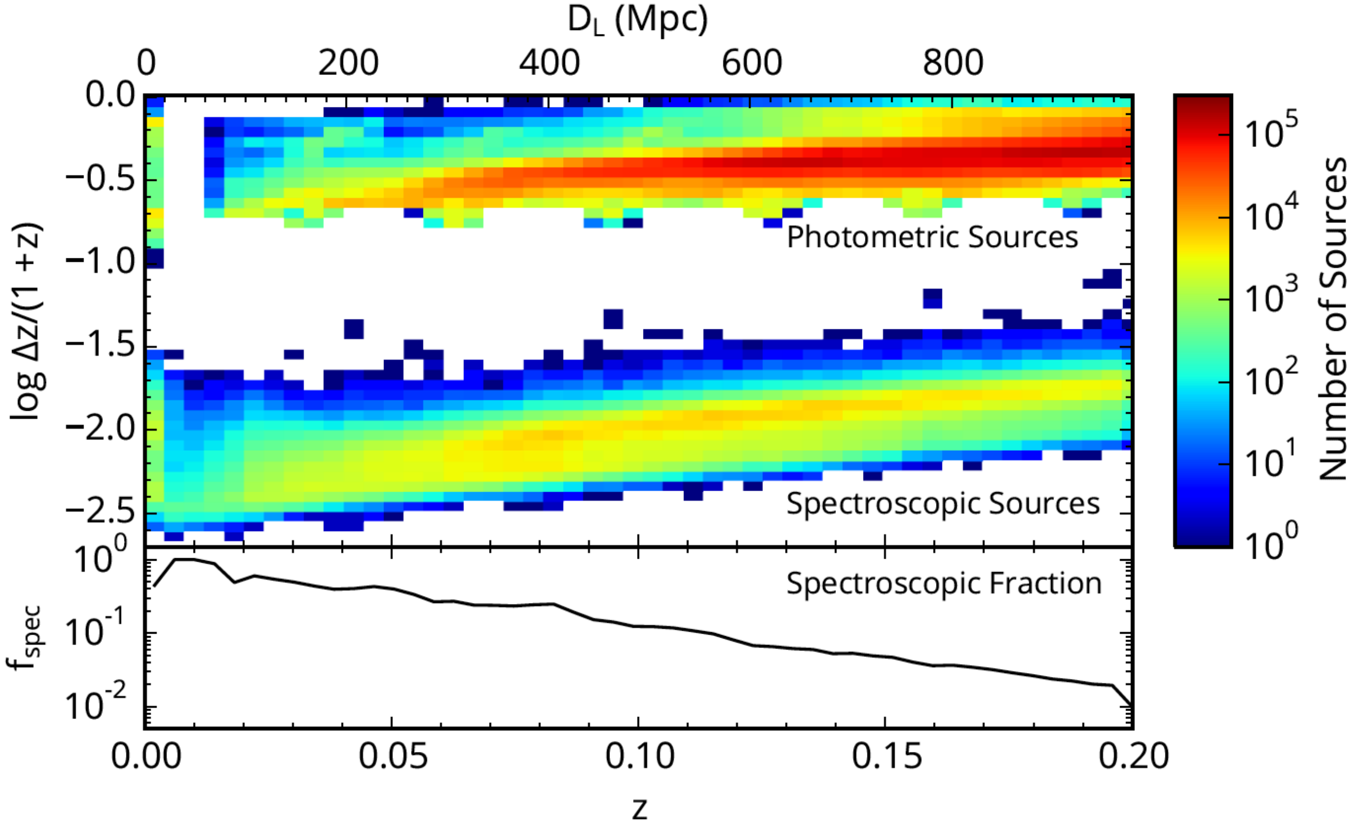
600 -> 10-20 sq. deg. (90% c.r.)

with KAGRA/LIGO India - a further factor of 4/2.8

[LVC, PRX 6, 041015 (2016); PRL 118 (2017), Gaebel et al, 1703.08988, 2017]

Today: Cross correlate GW volumes with Galaxy catalogs

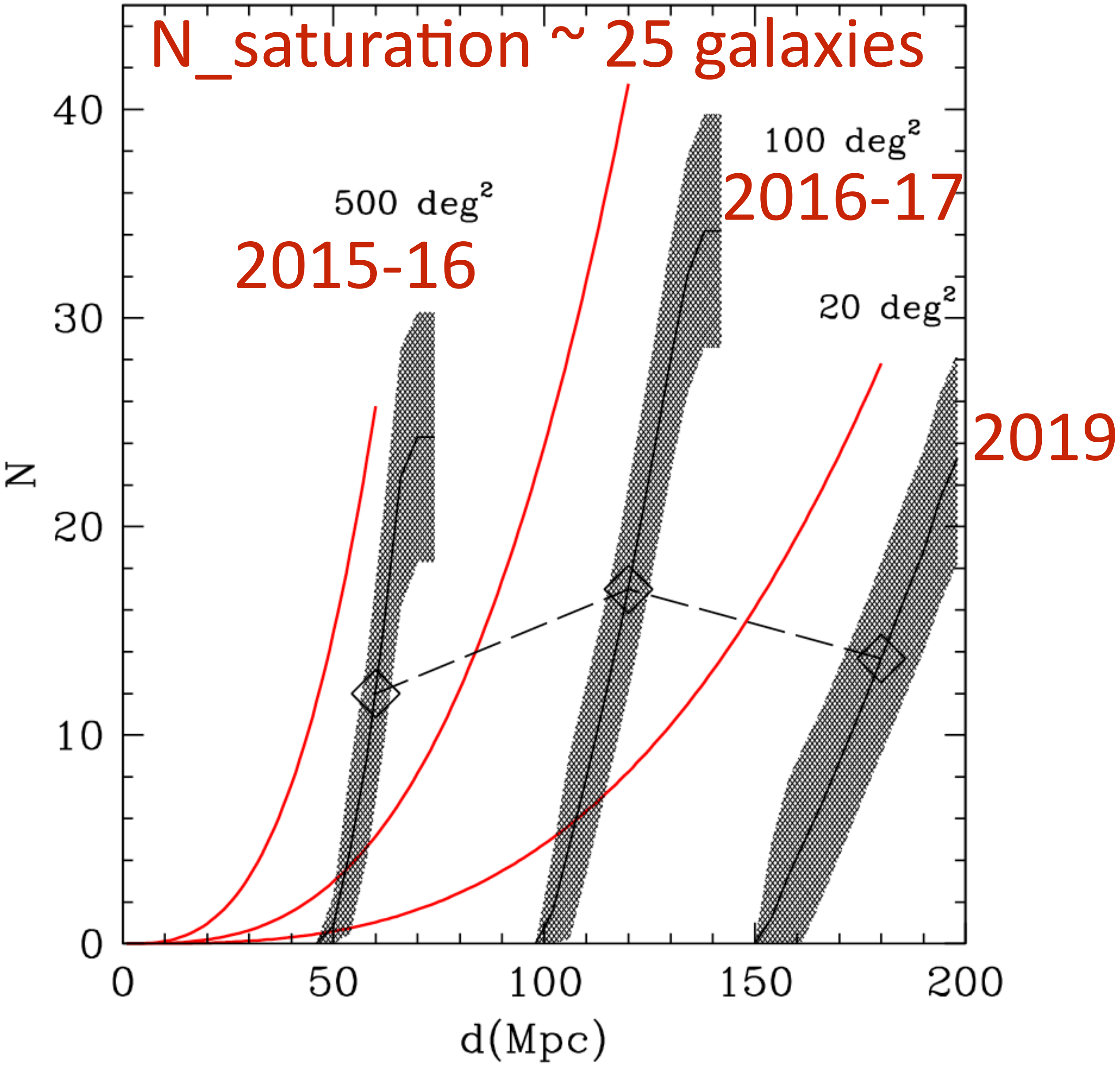
[Nissanke, Kasliwal et al. 2013, Singer, … SN, et al. 2016]



SDSS GW galaxy catalog
see https://astro.ru.nl/catalogs/sdss_gwgalcat/index.html

[Rahman, Nissanke + in prep]

brightest galaxies that produce 50% of the light

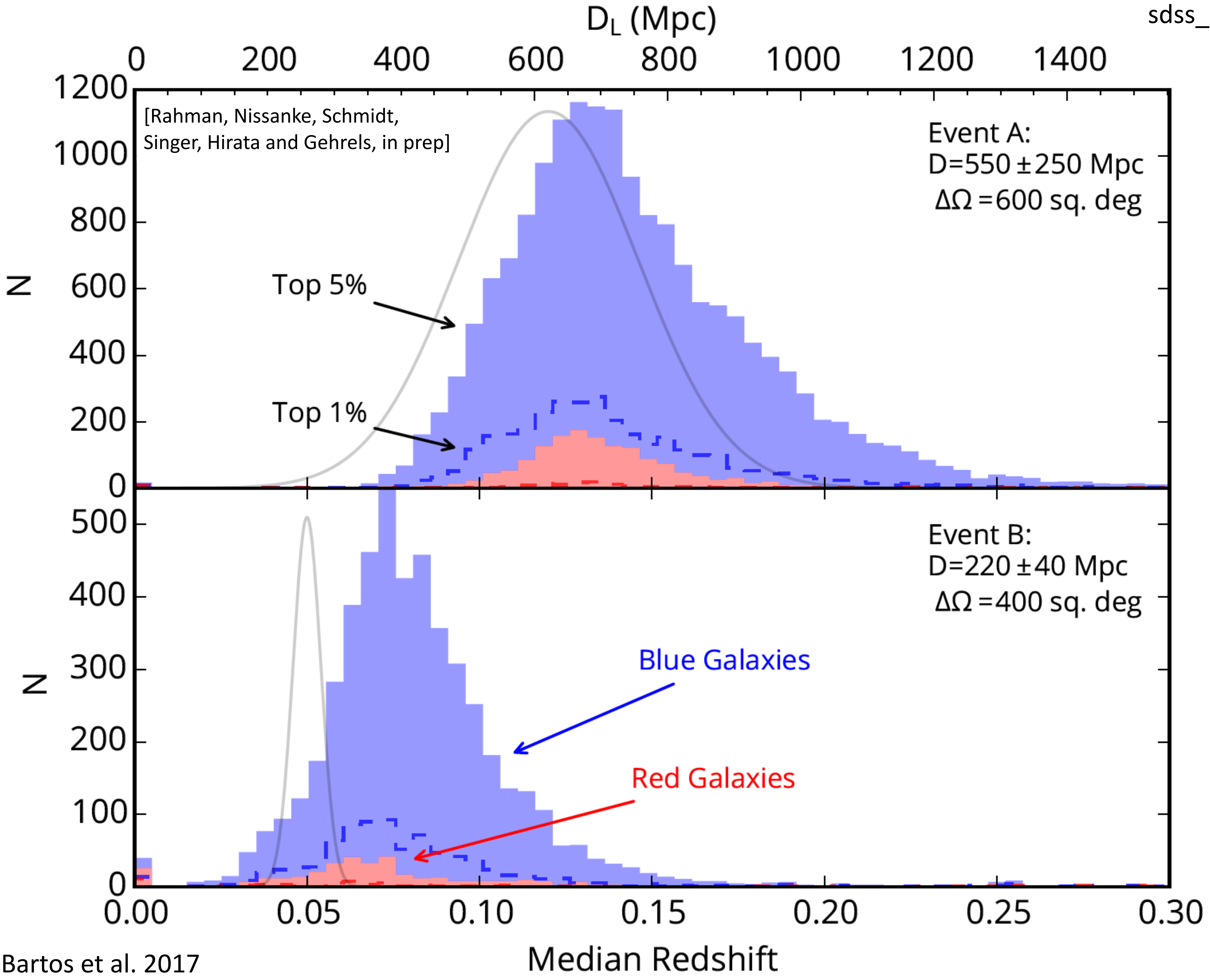


[Gehrels, Canizarro, … Nissanke + 2015]

Big data in Astronomy : Reduce astrophysical false positive transients by factor of 10-100s.

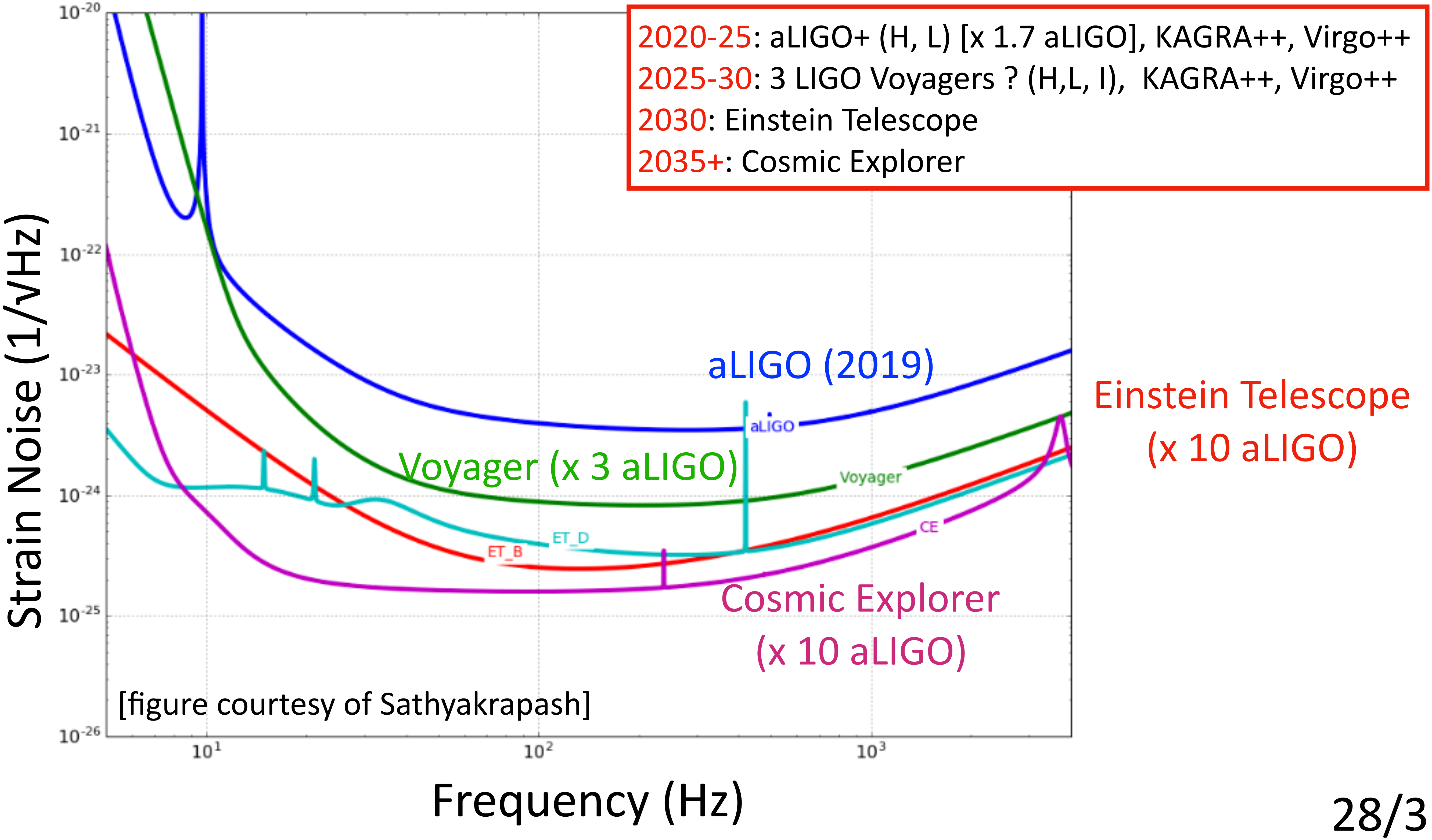
Statistical host galaxy demographics with no EM counterpart

SDSS GW galaxy catalog
see https://astro.ru.nl/catalogs/sdss_gwgalcat/index.html



see also Bartos et al. 2017

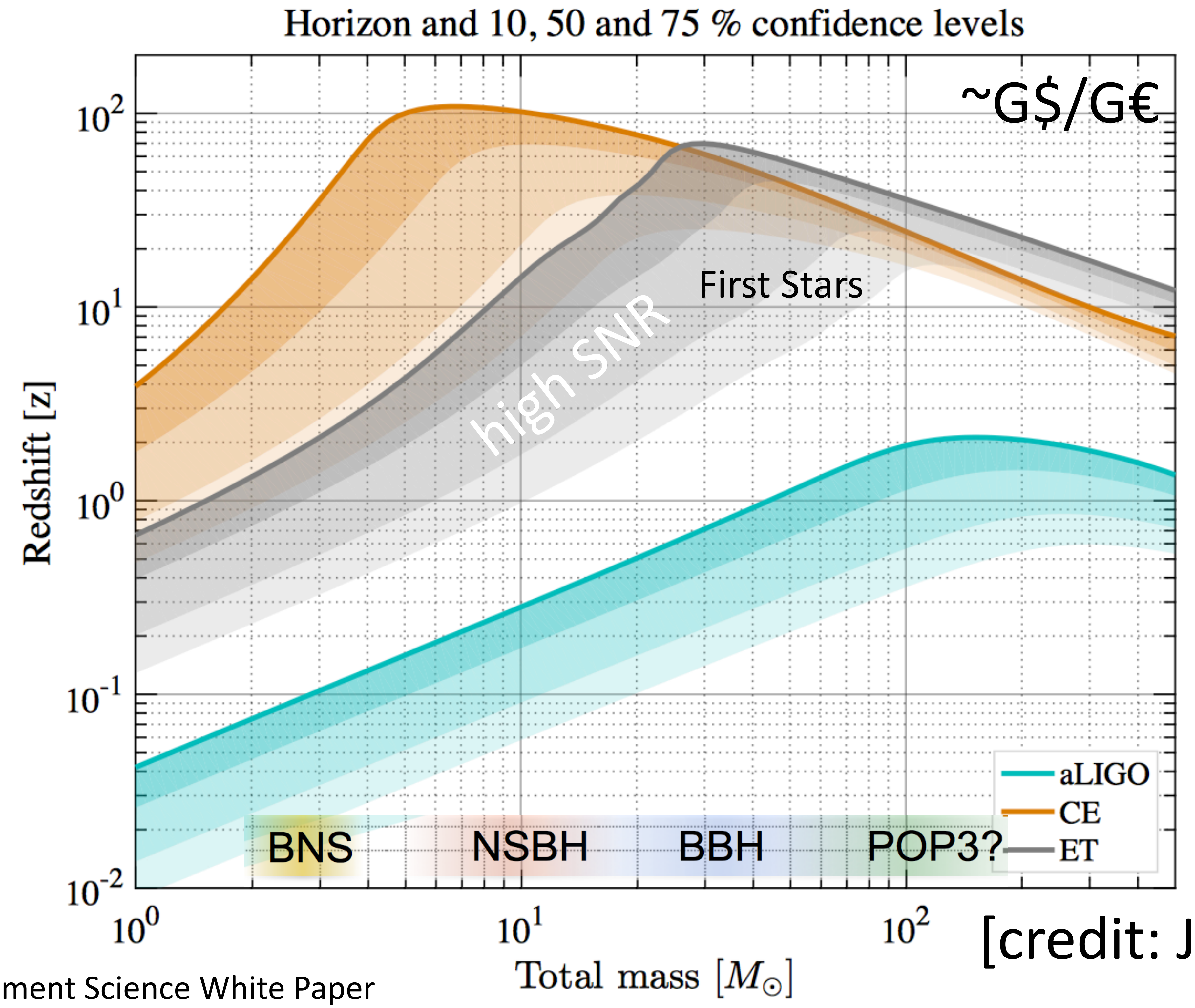
2020s-2030s: possible scenario for upgrades and new facilities



2020-25: aLIGO+ (H, L) [x 1.7 aLIGO], KAGRA++, Virgo++
2025-30: 3 LIGO Voyagers ? (H,L, I), KAGRA++, Virgo++
2030: Einstein Telescope
2035+: Cosmic Explorer

[figure courtesy of Sathyakrapash]

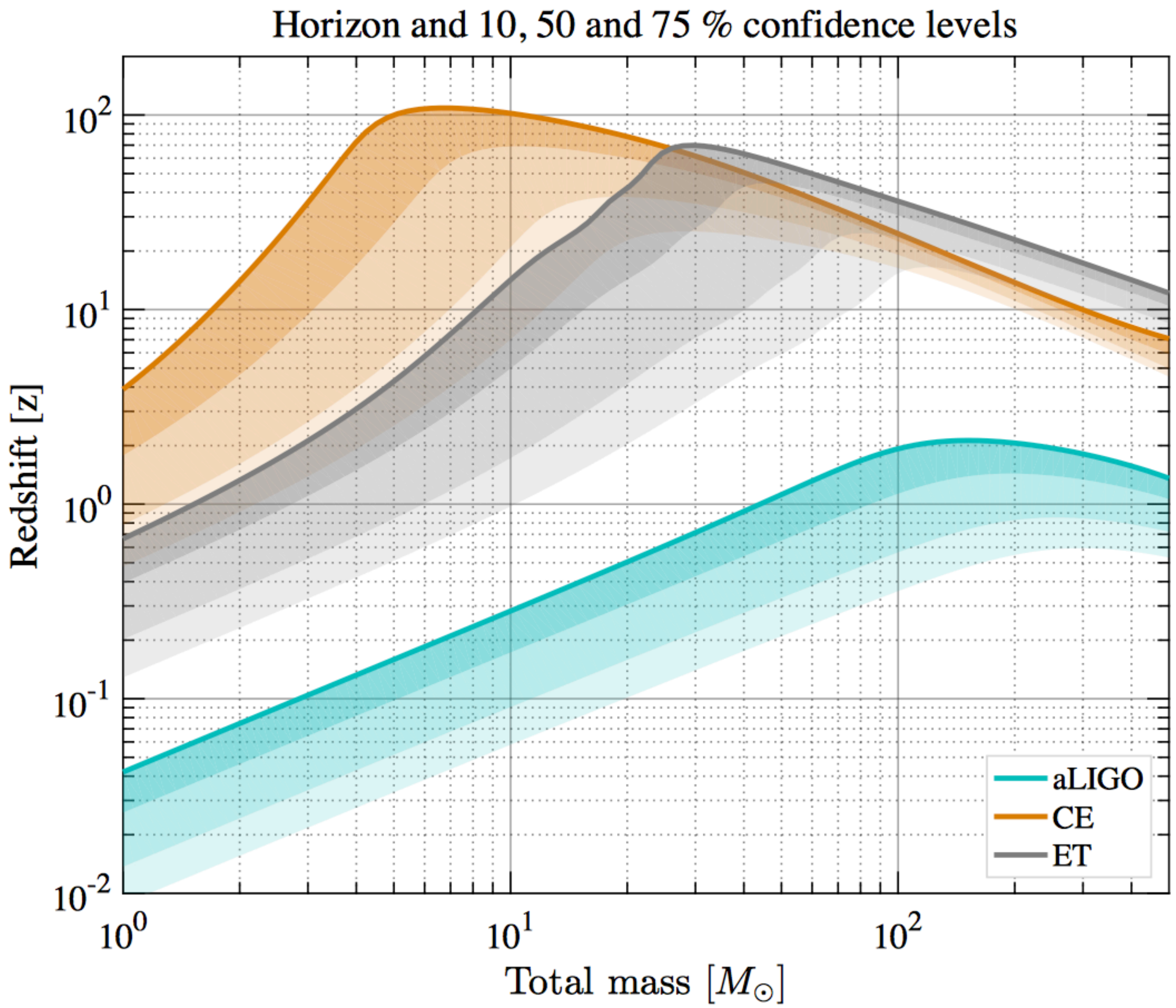
Einstein Telescope and Cosmic Explorer have cosmological reach



[credit: J. Miller, MIT]

See LSC Instrument Science White Paper
https://dcc.ligo.org/public/0125/T1600119/004/wp2016.pdf

Einstein Telescope and Cosmic Explorer have cosmological reach

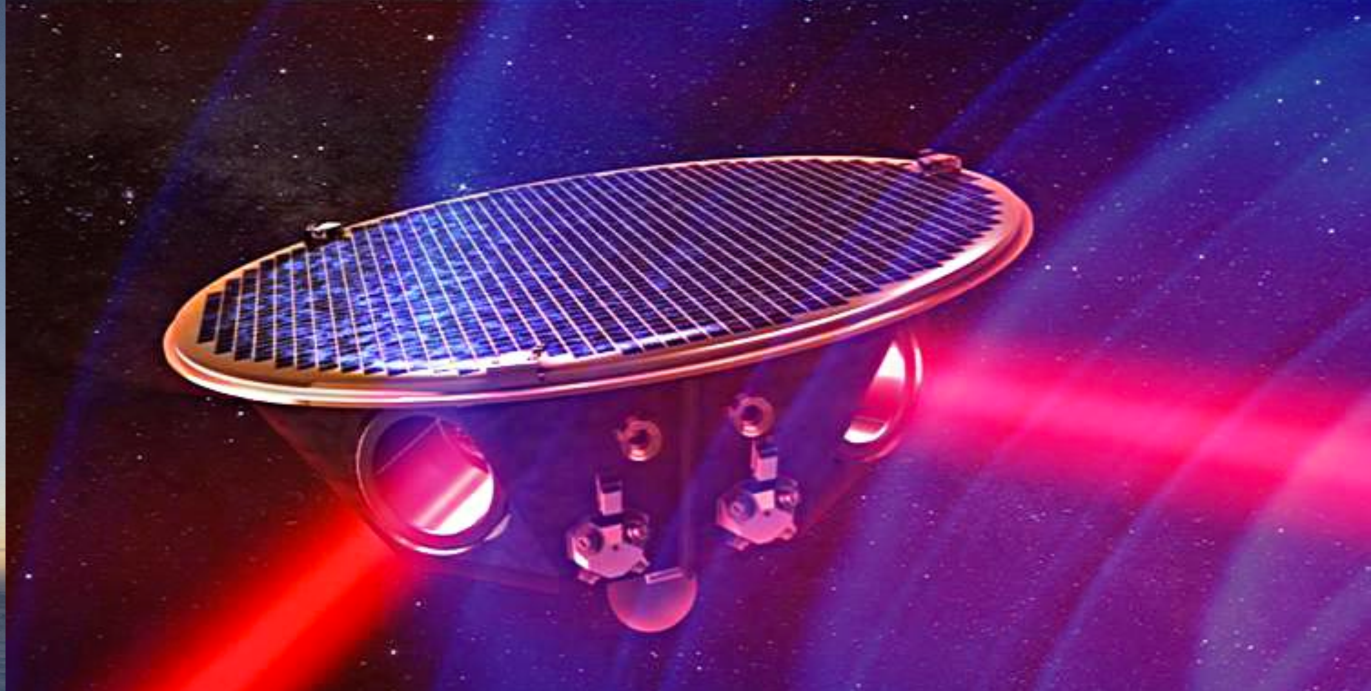


How well can we constrain SFR? Dependence on metallicity

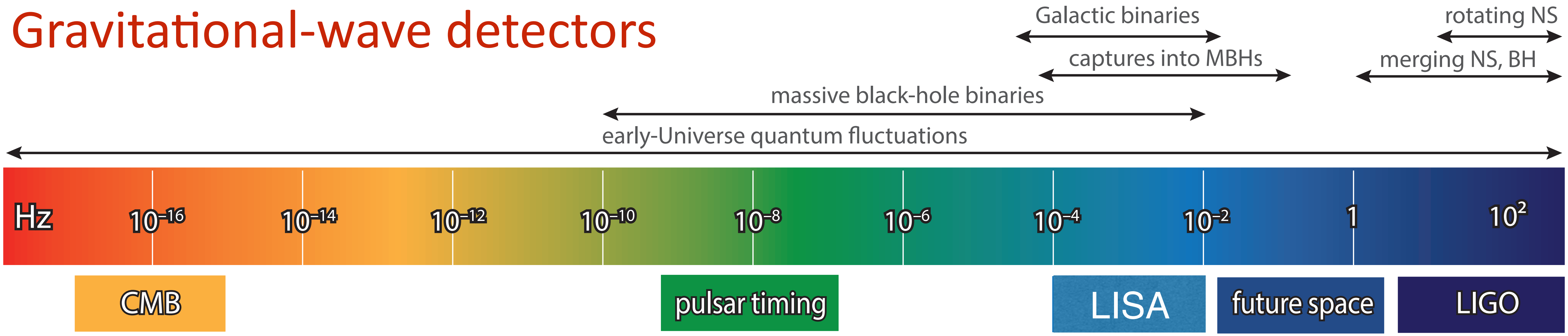
Cosmic (redshift-dependent) Merger Rate?

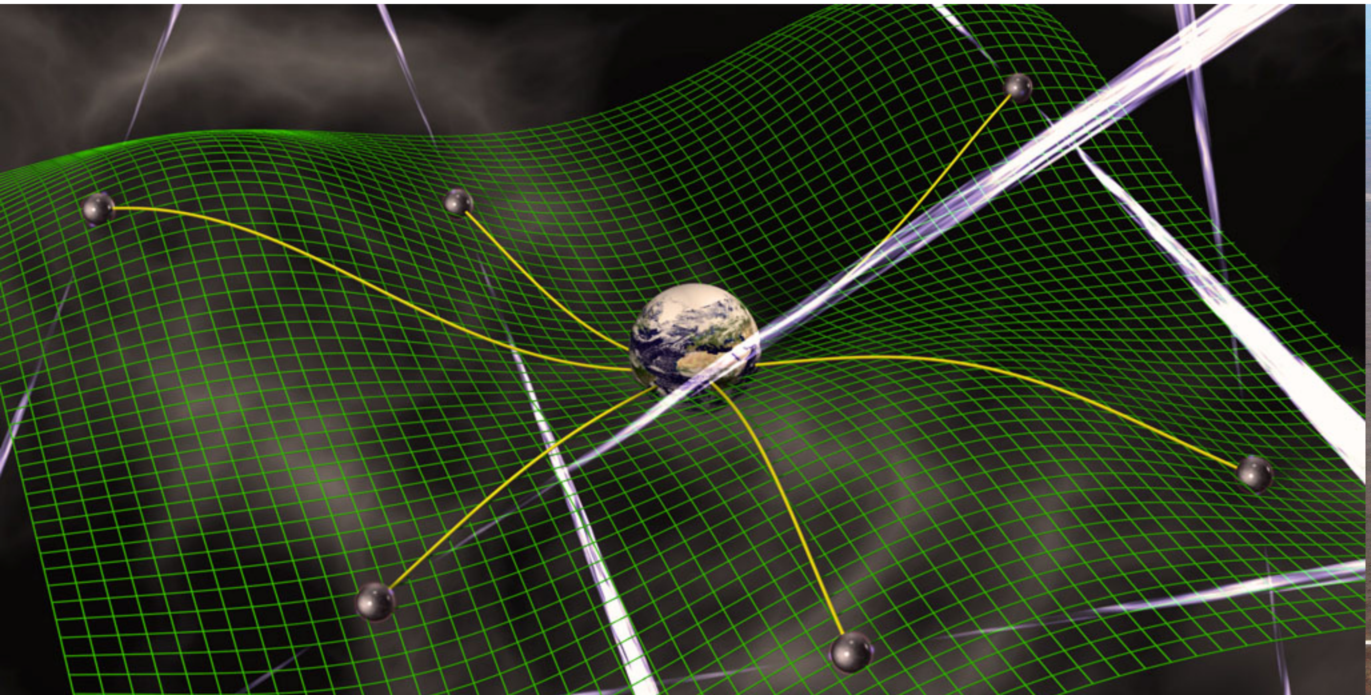
Mass gaps: NS and BH, intermediate BH desert?

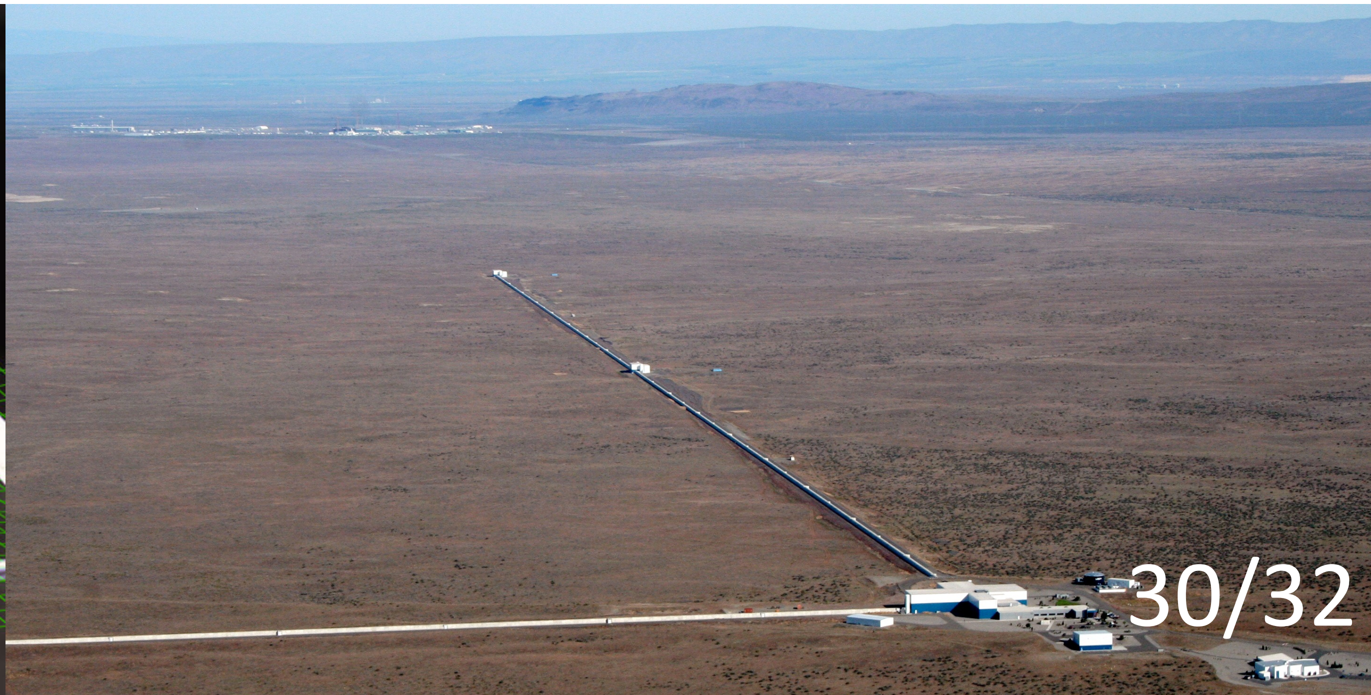
[slide courtesy of Michele Vallisneri]

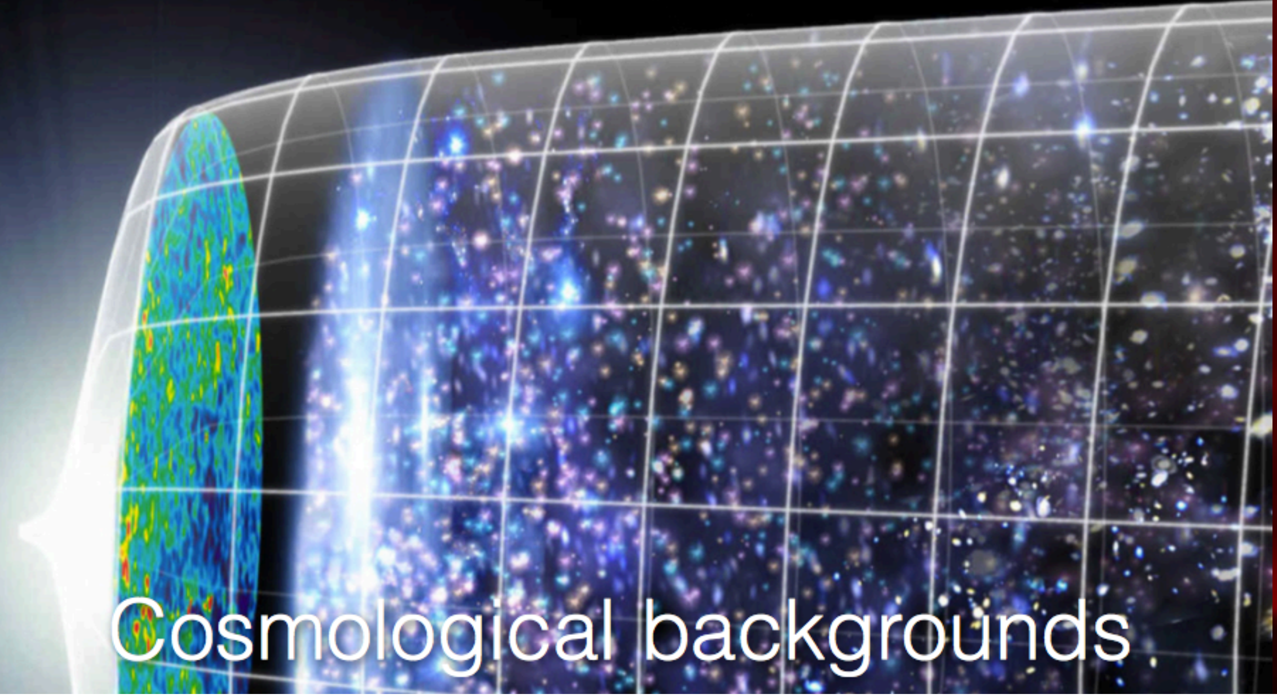


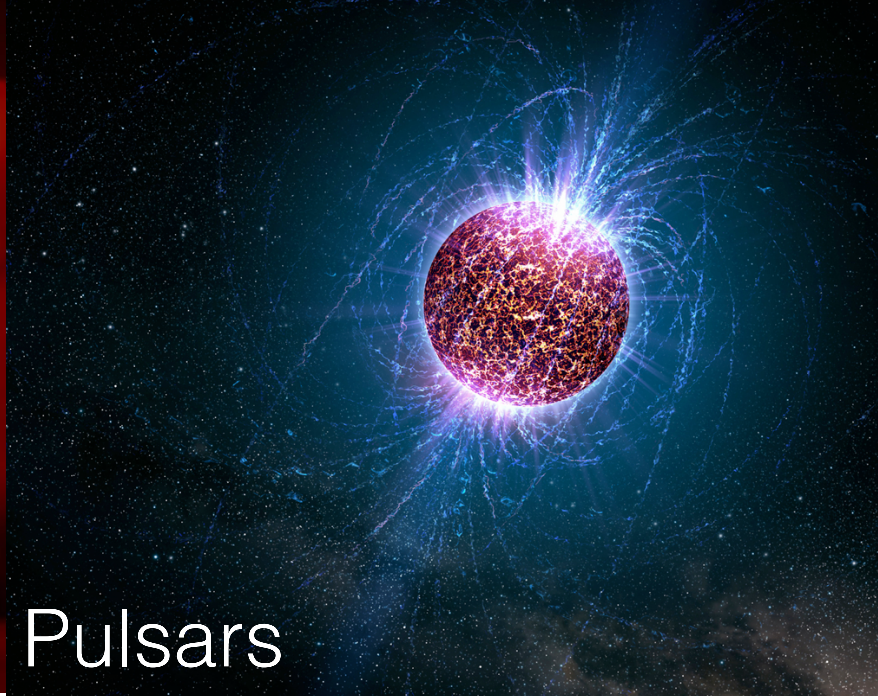
Gravitational-wave detectors



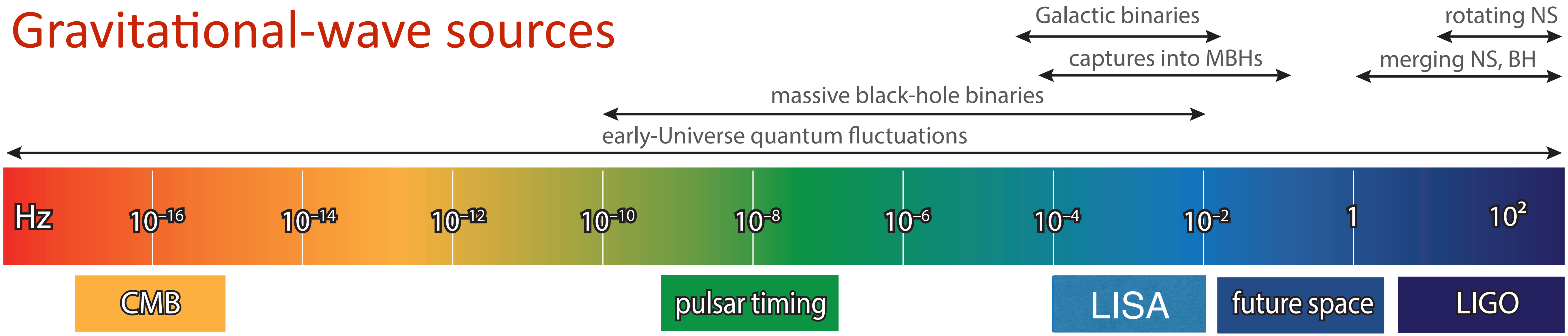








Gravitational-wave sources



Galactic binaries

rotating NS

captures into MBHs

merging NS, BH

massive black-hole binaries

early-Universe quantum fluctuations

Hz 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

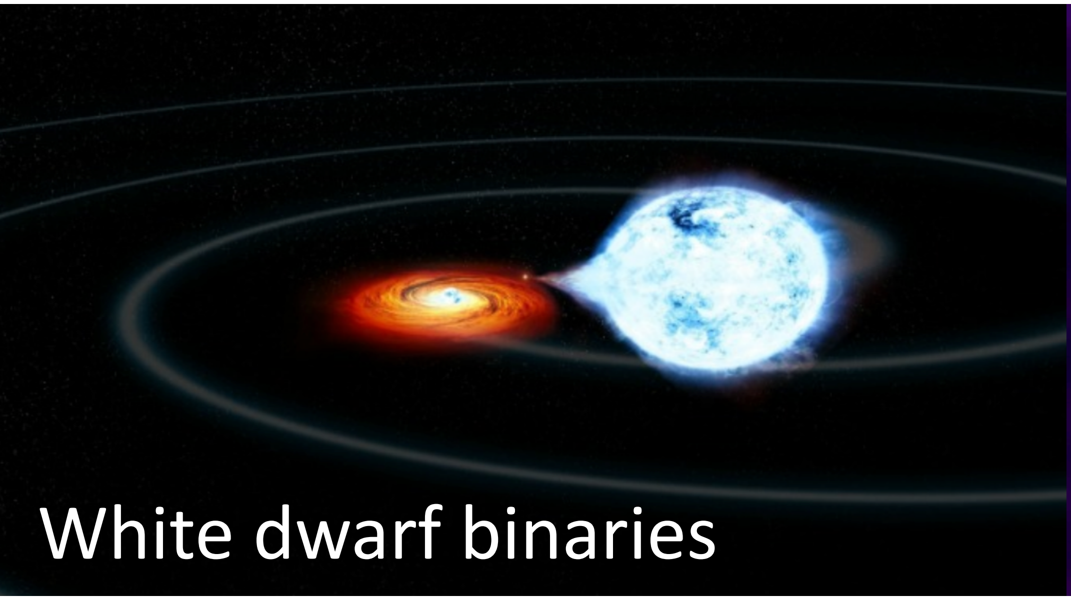
CMB

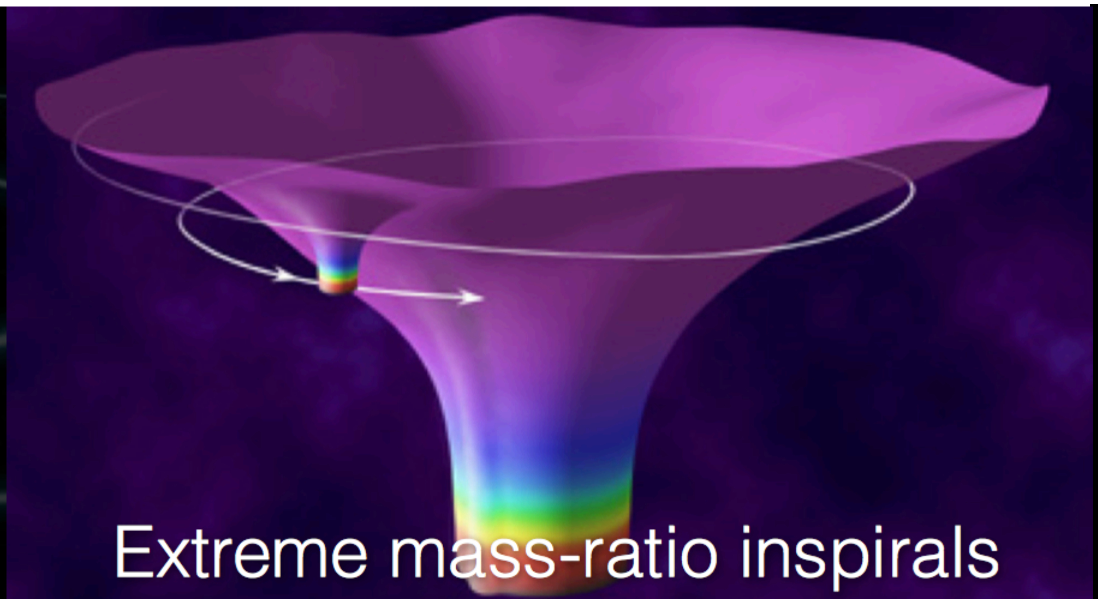
pulsar timing

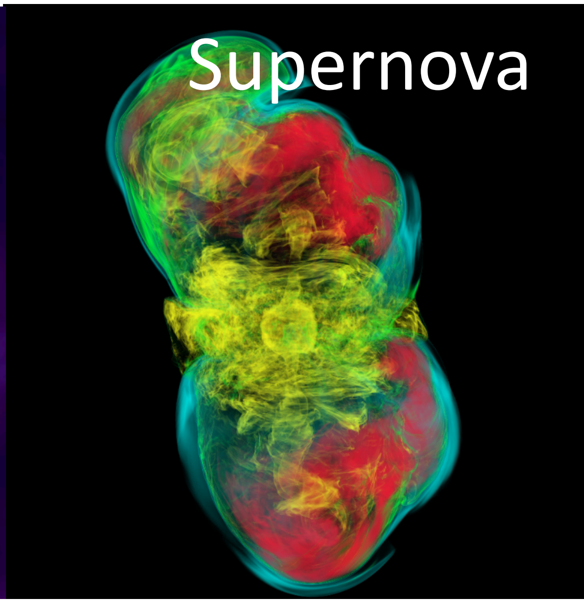
LISA

future space

LIGO







First-order phase transitions, superstring kink & cusps, inflationary signature, new sources!

The immediate future is loud and bright!

Immediately in the coming years : GW detector sensitivity & network increases => Tens of BBH mergers yr^{-1} and first GW-EM detections.

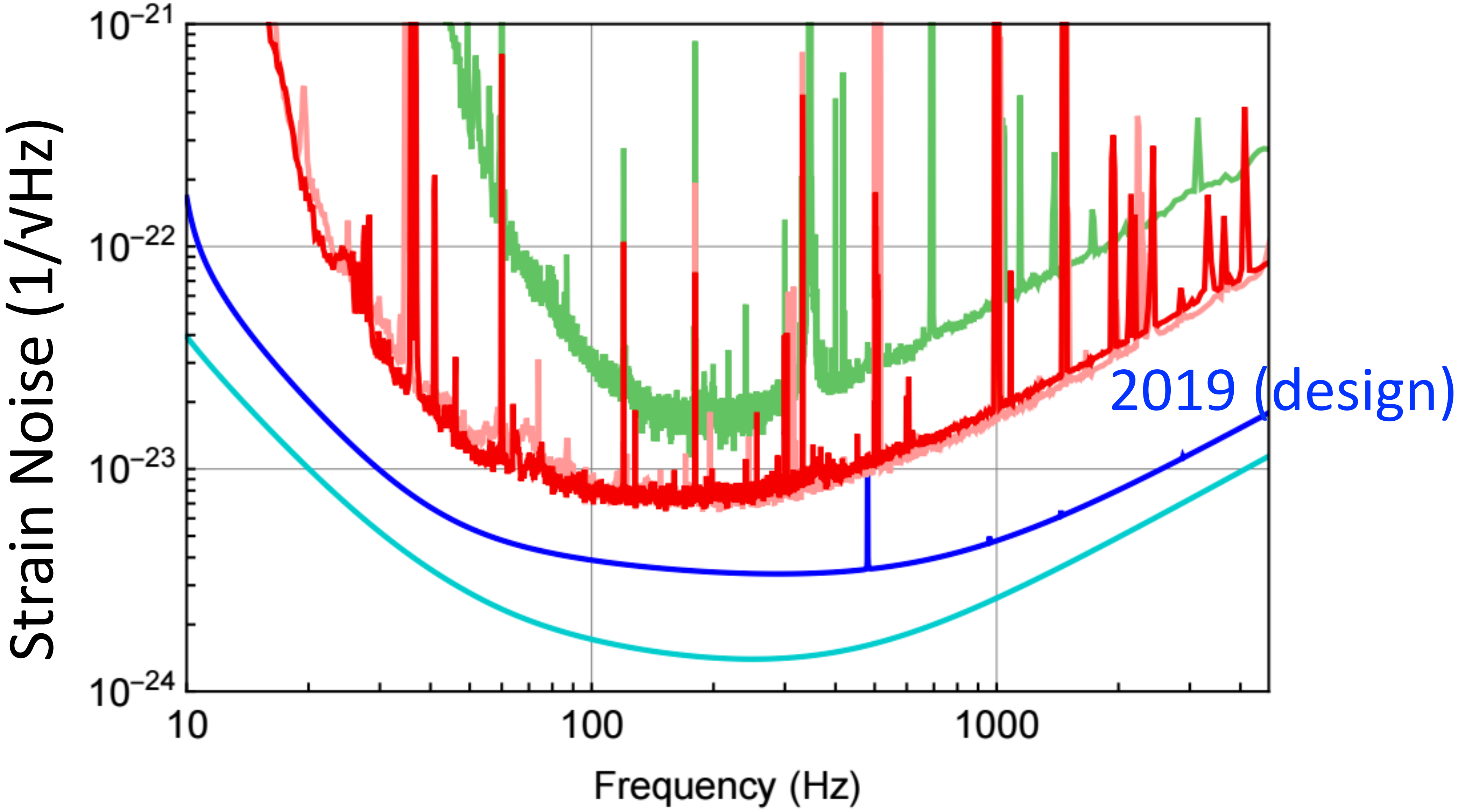
EM counterparts should provide key complementary information and break degeneracies in GW parameters: the redshift, host galaxy, energetics and orientation of the binary.

Key step for GW+EM: joint analysis for masses, spins, sky position and redshifts for populations of compact object mergers are necessary for astrophysics.

Beyond LIGO, Virgo era: Witness the opening of the entire GW spectrum with CMB, PTAs, LISA, new generation ground-based detectors …together with next generation of wide-field synoptic surveys LSST, SKA … and GMT/TMT/E-ELTs.

GWs are well-monitored and very accurate experiments

O1: 09/15-03/16 (51 days)



O2 Science Run: 11/16 - 08/17 (81 days as of 23rd June)
August 1st 2017: Virgo joined O2 science run!

[http://www.virgo-gw.eu]

GW: how many? how far?

[LIGO Scientific and Virgo Collaborations (LVC), Living Reviews in Relativity 19, 1, 2016]

Epoch		2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration		4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc	LIGO	40 – 60	60 – 75	75 – 90	105	105
	Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	200	200
	Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections		0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400

[LVC, ApJLetters 832, 2, L21, 2016]